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The magazine *for*, *by*, and *about* telescope makers!

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The magazine *for*, *by*, and *about* telescope makers!

Editor: Richard Berry
Associate Editor: Robert E. Cox

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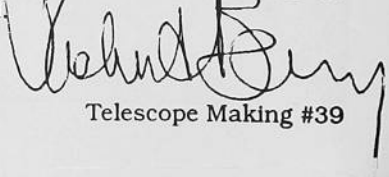
Cover: To make a precision optical surface you need a precise method of measuring its figure. With his eye to knife-edge, optician Peter Ceravolo surveys a large paraboloid using the Ross Null Test. When the surface is perfect, he will see a uniform null, just like the null a sphere makes in the class Foucault Test.

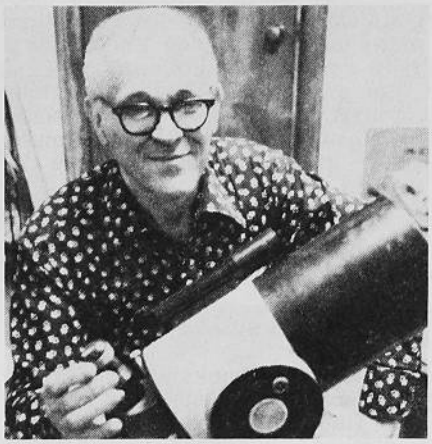
Editorial

As this issue of *Telescope Making* was in the final stages of preparation before publication, Mrs. Hilda Cox called with the news that Bob Cox had quietly passed away in the early evening hours of December 16. Those of us who had worked with Bob knew that the emphysema that had so strongly restricted his activities for the last two years would eventually claim his life, but had not expected the end so soon.

Two years ago, Bob phoned to ask me if I would consider running an unusual editorial on the health hazards of optical work. Unsuspecting, I said, of course. When the editorial arrived, it was immediately clear when he wrote, "opticians who work with diamond generating equipment may contract emphysema from inhaling the fine mist of glass, water, and oil these machine throw off," that Bob wasn't talking about just any optician. He was talking about himself. The editorial was published in *TM#34*.

Bob was one of a kind. I can never forget his energy, enthusiasm, and the burning desire to help his fellow man that drove him. I'll also remember Bob as the practical joker, the terrible punster, and the speaker with every audience eating out of his hand. Optics may have been his subject, but it was the man whom we loved. He will be missed.





Robert E. Cox
1917—1989

Letters

A Story of Commercial Optics

Dear Richard/ First off, I want to let you know that I thoroughly enjoy *Telescope Making* magazine and what it has to offer. I would like to also make a few comments about commercial optics since I have had some unfortunate experiences with one company in particular. I am happy to see that the problem of poor quality commercial optics is being discussed and brought out into the open in your magazine.

In the early 80s I bough a 10-inch research series reflector from a reputable commercial manufacturer. I was more or less happy with the performance of the scope since I had never had a look through a first class instrument to compare. A couple of years after buying the scope, I have the primary mirror to a local optician to have it re-coated. The optician called me a couple of days later to give me the bad news. I was shocked to discover that the mirror was only 50% corrected. The surface was smooth but not fully parabolized. I let the optician refigure the mirror and after reinstalling it into the scope the improvement in performance was outstanding. I could see detail on the moon and planets like never before. I wrote the company that made the telescope to let them know of the situation and was not even granted the consideration of a reply.

About 3 years ago, I began construction of a 14.3-inch f/4 Newtonian using a superb primary mirror crafted by Peter Ceravolo. Because of the quality of the primary mirror, I wanted a good secondary mirror to compliment the system. I ordered an advertised 1/10-wave quality 4-inch elliptical flat from the same company that made my previous 10-inch scope. They use this size mirror in their 16-inch f/4.5 telescope line. I took a chance that my previous problem had been an isolated incident. The mirror arrived and I promptly had Peter test it. Again, I was in for a disappointment. The mirror was inferior; it did not even come close to the advertised tenth-wave quality!

I called the supplier to inform them of the problem and was promised that an advertised quality flat would be returned to me within a couple of weeks. It took 3 months to receive the replacement mirror. The second mirror was worse than the first! I felt that there was no sense in continuing this course of action as I had lost all confidence in the company's ability to deliver the quality I wanted. I had a local optician refigure the mirror to the flatness I desired. This doubled the cost of the flat mirror not to mention the mailing costs and other hassles.

I again wrote the company stating how disappointed in them I was and that I thought if they could not deliver a mirror of advertised quality, they were possibly guilty of false advertising. I also stated that I felt they were taking advantage of the average amateur astronomer since many do not have access to opticians for optic testing or have the necessary skill to test optics themselves. There is another interesting point I must bring up. I have noticed that the company that I have been referring to has changed their advertising claims in the magazine ads they run now. The do not give surface quality quotes anymore in the ads for the flat mirrors used in the telescope line I mentioned.

To me this indicates that something was wrong and that perhaps they were not delivering the advertised quality on a consistent basis as claimed. Since they now don't advertise a quality that they must live up to consistently, I really wonder what quality is actually being produce.

If commercial companies do not give claim of optical quality in their ads but rather give a"satisfaction guaranteed or money refunded" claim, the purchaser does not have much room to complain if the optics do not deliver as expected since they can be re-

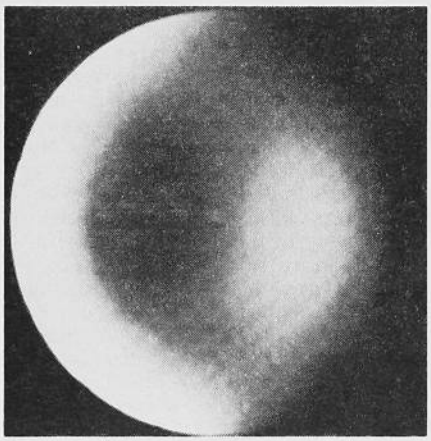
Letters

turned. I have some concerns over this type of policy since the possibility exists that a high standard may not be maintained on a consistent basis. This could possibly result in many sets of substandard optics being produced and sold to unsuspecting amateurs who will then get substandard images in their telescopes.

The old saying, "you get what you pay" is justified in optics. Once you have used a scope with excellent optics you will never be satisfied with anything else. I do not mind manufacturers asking a fair price for quality optics — *providing they are delivering quality optics.* I can even accept the fact that a poor mirror may slip through the quality control checks from time to time. But such failures should be the exception rather than the rule.

I would rather pay extra for excellent optics than for all the bells and whistles that many telescope manufacturers are using to sell telescopes these days. The bells and whistles are useless if the images in the main telescope are crappy. I believe the emphasis of the manufacturer should be on optics quality and stability, not options. When it comes to commercial optics, it's still "the buyer beware."

Bryce Heartwell
1140 105 Avenue, SW
Calgary, Alberta
CANADA T2W 0B1



You Can Do It

Dear Richard/ I've just completed my first "handmade" telescope, a 20-inch f/4 called MOONSHINE. Using your book along with Texereau, Howard and others, an arduous task became much easier.

I thought you might like seeing a focogram of the aluminized mirror taken with unhypered 2415 and developed in D-19 for four minutes. It was printed in Dektol on Kodak Polycontrast with no filters and an exposure of three seconds. The exposure of the mirror itself was five seconds.

The "smear" on the mirror is the collimating dot in the center and it is indeed smeared. In comparing the focogram with page 80 of Texereau, I am pretty happy with mine. The mirror is 1/16-wave on the wavefront.

Can an amateur do a big, short mirror first? Yep! Can he do it in reasonable amounts of time? I very much doubt it — the job took me 20 months.

Leon Knott
Museum of York County
4621 Mt. Gallant Rd.
Rock Hill, SC 29730

Titanium and Silicon

TM Readers/ Thanks for your comments and suggestions about my article, "Titanium Tubed and Computer Controlled," published in *Telescope Making #38* and the cassette tape for my program. The following comments are things I should have mentioned in the article:

I wrote the program on my CoCo 1. While no problems have been experienced on my thirty dollar spare CoCo 2, I do anticipate that if you try to run the program on a CoCo 3, there will be problems related to address calls in the machine language subroutines and the peripheral interface adapter. Since I don't own a CoCo 3, you may have to do some digging into the innards of your CoCo 3, if that's what you have.

To make both pushbuttons work on my deluxe RAdio Shack joystick, I had to perform some surgery to the joystick connectors in my CoCos. Namely, the unused top center pin of each connector must be cut from its grounded point and connected via a jumper wire to pin 4 of the opposite connector. Note that this modification may void your warranty, or worse, that Radio Shack may refuse to service such a modified unit.

In case it wasn't clear in the article, this system is made for equatorially mounted scopes only; if you want to have a smart Dob, I would suggest you investigate the Lumicon Sky Vector as an alternative. Also, the constants used in the program to determine the number of steps per move must, of course, be altered to fit your gearing ratios.

Since writing the article for *TM#38*, I have made an addition to the program: a planetary emphemeris routine calculates the positions of all the planets for the night's observing session. The addition made the observing program so long that storage can now be made only on tape, even though a "PCLEARO" POKE is done in the initializing program (there is no memory available for the disk operating system).

If I haven't scared you off and you still want to invest a year or so in building a system, then I will send you one of Radio Shack's computer grade tapes with the initializing and observing programs duplicated on both sides, for redundancy. (Twenty dollars should cover the cost of the tape and my time. Besides, I really hate doing tape backups!) If you have any other questions, please feel free to write or, maybe better, to call. My number is (704) 536-9595. Please call only between 8 and 10 PM EST.

Ron Simpson
7626 Gayle Avenue
Charlotte, NC 28112

Overcome by Big Mirror

Gentlemen/ A little over a year ago, my husband and I saw an ad in Telescope Making which said "61-inch mirror for free to person who will come get it." I knew this could possibly be my husband's dream come true, so I borrowed the money for the trip and sent him on his way. When he got back with the mirror, I realized this was the largest piece of glass I had ever seen. It was 61 inches across and a foot thick.

We teach astronomy to students in the schools around our area. Living in southeastern Oklahoma there isn't any place around here where our schools and universities can do their observing unless we offer our scopes. My husband's dream is to build this telescope for amateur astronomers and students to use.

I read articles all the time about promoting astronomy in schools. Well, my husband's trying his best. If he even gets this together, he'll have to put a plaque on it thanking our neighboring salvage yard.

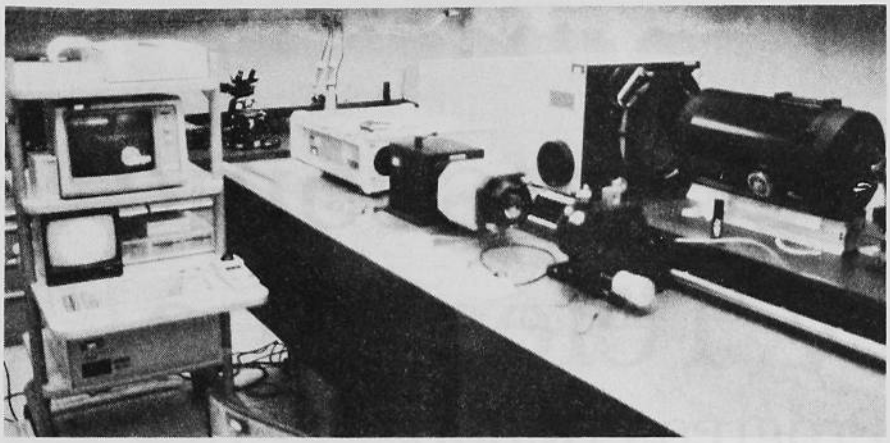
What he needs is help and lots of it. He doesn't want any money out of this at all. He wants a place for out students to be able to observe and learn about astronomy. We think we can get a place donated for the site, but to put it into operation takes money and a lot of help. The reason for this letter is that I thought maybe if we give time on the 61", just maybe we could get enough to put it together. We had one offer to put it in operation, but if we had taken the offer, we would have lost control and that meant selling time to big astronomers who can pay and that left out the amateurs, and schools.

We don't know where to turn. If you could give us help in trying to figure out how to put it into operation, we would sincerely appreciate it.

Jevita Black
Star Rt. Box D-2
Lone Grove, OK 73443

Glass Suppliers Wanted!

Dear Richard/ There seem to be no suppliers of optical glass listed in



your Blue Pages. It is frustrating to read articles on refractor making without having any idea of where to obtain the required optical glass.

I can guess that optical glass suppliers probably lose money every time they deal with an amateur optician, and that many suppliers don't really want our business. But must publication of addresses and telephone number bring an avalanche of inquiries, thereby forcing the companies to abandon all dealings with amateurs in order to retain their corporate sanity? Isn't there even one supplier offering a few sets of blanks for the amateur refractor maker?

Herbert Highstone
P.O. Box 249
Monte Rio, CA 95462

– In the past, small go-between firms such as Norman Remer Optics supplied refractor kits. More recently, individuals with connections in the optics industry such as John Gregory and Bob Schalck have organized glass buys for special projects. I am sure that Mr. Highstone is not alone in his search for lens blanks; Telescope Making *would appreciate hearing from all firms sell blanks to amateurs. – RLB*

Let's Get Interferometric

Dear Richard/ My new job at the National Research Council is proving to be lots of fun. Once of the biggest advantages to working here is having access to sexy instrumentation like a Zygo interferometer. The setup is a double pass one, so the wavefront errors are doubled.

The picture show a 10-inch and a 4-inch Meade telescope. The 10 inch is Meade's second effort to provide an acceptable telescope to the buyer. Meade even told the dealer that I would be impressed with its quality! The zone at the edge traverses with the width of a light band, and since this is a double pass arrangement, it corresponds to a 1/2-wave error on the wavefront. This is the worst possible place to have such an error because the zone is at the edge. The 4-incher has a 1/2-wave wavefront edge roll, but its wavefront is somewhat smoother.

Peter Ceravolo
P.O. Box 57
Metcalfe, Ontario
KOA 2PO
CANADA

Brass Tubing for Refractors!

Hi Richard/ I spoke with Roy Johnstone in San Fran regarding brass tubing for refractors. He has no problem dealing with inquiries from TMs. There is no "price list" in that they really aren't a retailer. (And also with metal price fluctuations.) Roy normally has up to 6 inches I.D. on hand and has access to other, larger sizes.

Roy Johnston
Bay Sales & Manufacturing Co.
1429 Wallace Avenue
San Francisco, CA 94124

As I said, Roy seems very willing to work with the requirements of telescope makers. The phone number is (415) 822-9777.

Larry Myers
9004 Pinfield Court
Elk Grove, CA 95758

Thinking BIG!

Dear Telescope Maker/ An organization has been recently formed in the San Francisco Bay Area to build a 72-inch computer-controlled telescope. I'd like to fill you in on our first steps and to encourage you to get involved with the project. While the actual construction of the telescope will be born mainly by local people, Group 70 plans an instrument that will be available for use by both amateur and professional astronomers across the country. Thus, we're now soliciting input from people likely to use this telescope when it is completed and housed – which we guess will be about 1997.

Basically, Group 70 formed to take advantage of the availability of a surplus Pyrex mirror blank, cast by Corning in the late 1930s, which was offered for sale by FAR, the Fund for Astrophysical Research. With encouraging promptness, the group raised about $30,000 to buy the blank. A Group 70 representative was sent to Australia to inspect the disk, which proved to be in excellent condition (and closer to 72 than 70 inches in diameter). Thus, the organization went ahead and purchased the glass for $25,000. Shipping it to the States will take about 6 months.

Group 70 is a non-profit corporation. There are currently about 40 members, and 30 or so are founding members who made individual contributions of $1,000. Local astronomy clubs are considering the lead of the San Jose Astronomical Association, which has committed to a $1,000 founding membership.

Groups 70's confidence stems much from the success of the 30-inch Fremont Park telescope and observatory, which were completed several years ago by Bay Area amateurs. This excellent facility is used mainly for public education. Many of the individuals involved with the Freemont Peak project are now involved with Group 70.

Please feel free to contact me or another Group 70 member for additional information. You might like a copy of Group 70's mission statement, which is presently being prepared and which will clarify the opportunities we expect the telescope to offer.

John Briggs
100 Oak Rim Way, 11C
Los Gatos, CA 95032

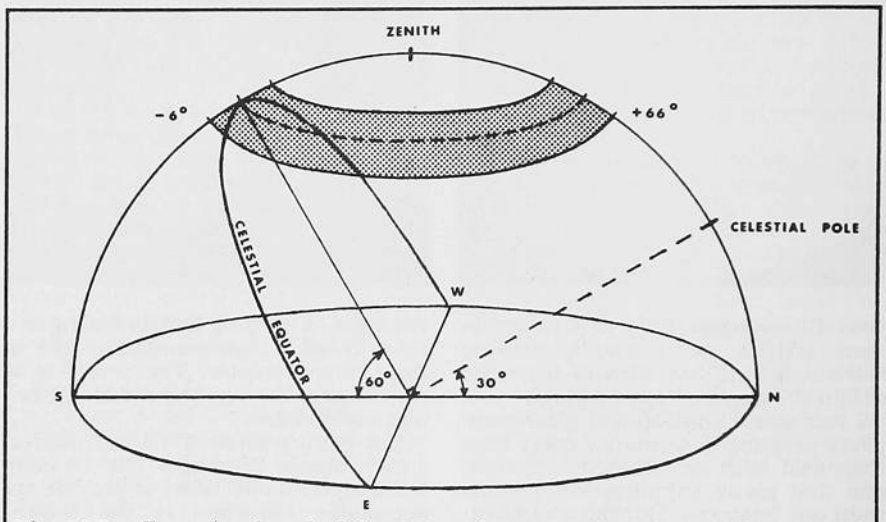
The Spectroscopic Survey Telescope

A Progress Report

In the basement of Osmond Laboratory at Pennsylvania State University, the mirrors for a remarkable new giant-aperture telescope are being fabricated. When finished sometime in the 1990s, they will comprise the eight-meter diameter Spectroscopic Survey Telescope, or SST. It will be the largest instrument ever dedicated exclusively to astronomy's most powerful investigative tool — spectroscopy.

Under the exceptionally dark skies of McDonald Observatory, this mammoth light collector will record high-resolution spectra of stars, quasars and galaxies down to twentieth magnitude. Yet, all of this will be accomplished on a miniscule budget.

This unusual professional telescope may suggest novel and interesting possibilities to amateur telescope makers. For example, clubs might consider mounting a very large, well-supported thin mirror in an all-azimuth, restricted-altitude mounting with a CCD chip at the focus. Under computer control, observers could track and image very faint celestial objects. So let your imagination go!



The SST will reach a band of sky 12° wide centered on the zenith. As Earth rotates, the SST will do spectroscopic work on stars from -6° to +66°.

A Most Unusual Mount

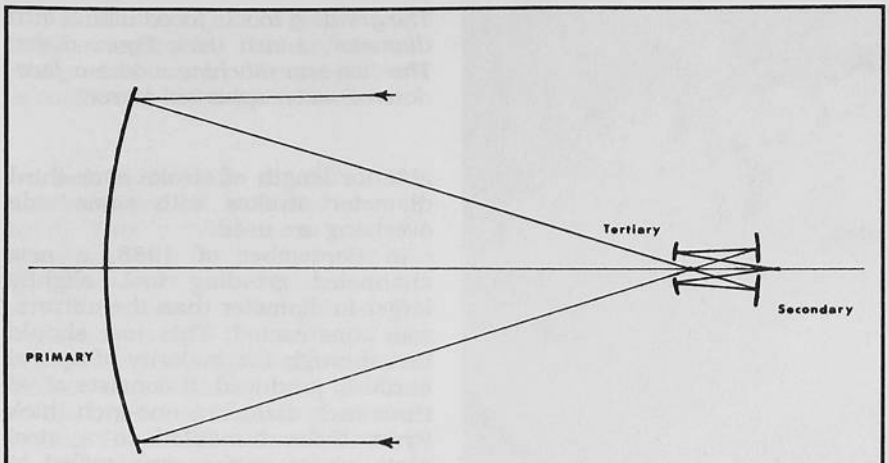
The most startling feature of the SST is its unusual mount. Instead of tracking sky objects using equatorial or alt-azimuth drives, the SST will remain fixed at an angle of thirty degrees from the zenith (although allowed to rotate 360 degrees in azimuth). How, then, can it make extended observations?

The secret behind the telescope's mount lies with its movable detector. Unlike conventional telescopes, whose detectors are fixed but whose supporting tubes must be guided on the stars, the SST's detector will move while the telescope tube remains stationary. Both the detector and image correctors will be computer-driven on two independent axes. Tracking is feasible over a range of six degrees from the axial image point. Actually, twin detectors will examine two different objects at once, doubling the telescope's efficiency.

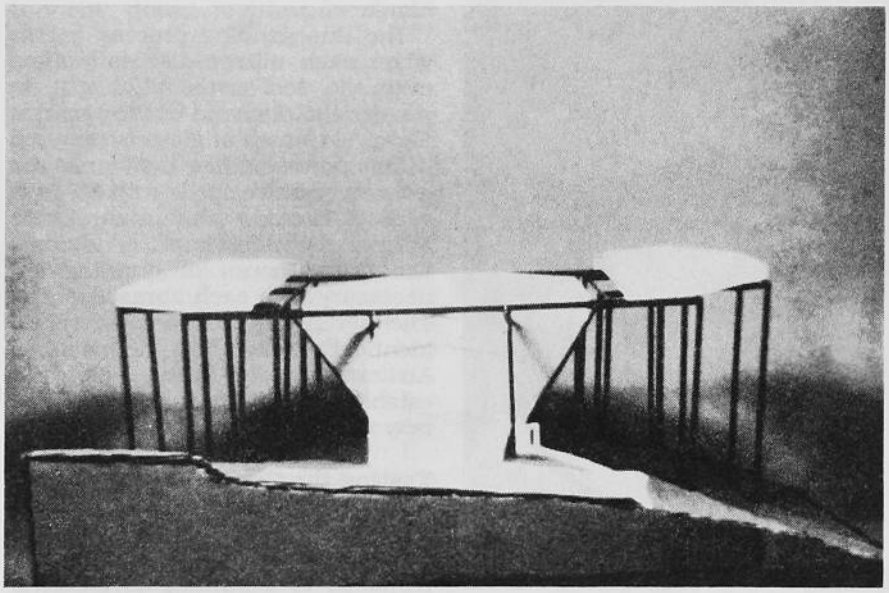
The telescope will be able to follow any object in a band of sky twelve degrees wide centered thirty degrees from the zenith; that is, at all azimuths and at elevations between 54 and 66 degrees above the horizon. Objects are tracked as they rise or set through this ring of sky. At the latitude of McDonald Observatory (roughly 30 degrees north), objects with declinations from -6 to +66 degrees will pass through the viewing zone.

The mean viewing period will be close to an hour, but varies from forty-five minutes near the celestial equator to almost two hours near the pole. This much leeway should allow observers plenty of time to collect the light they need.

This tracking method, unheard of in optical astronomy, has been practiced for years by radio astronomers with the famous Arecibo dish in Puerto Rico. (The Spacewatch Camera in Arizona operates in a truly fixed mode that exploits the earth's rotation. That instrument may also be pointed to any desired altitude.)



Light from the multi-mirror primary is brought to a focus by secondary and tertiary mirrors, then piped to the spectrograph through a fiber-optic cable.



An unusual flat-roof observatory designed to allow rapid thermalization of the optics and their support structures will house the SST.

The purpose of the SST design – apart from allowing major cost reduction – is to overcome the varying effects of gravitational stress on the mirror support system. Moving the telescope to different altitudes would flex this framework enough to destroy the image quality. By supporting the optics under constant load, no further changes should be produced. Hence, the need to make sophisticated, real-time corrections to the optical alignment is eliminated.

The creative spark behind this innovative concept came from Penn State astronomers Lawrence W. Ramsey and Daniel A. Weedman. With colleagues at the University of Texas in Austin, particularly telescope designer Dr. Frank Ray, they are now refining the optical and mechanical systems while fundraising efforts proceed.

The Spectroscopic Survey Telescope is expected to cost only $6 million – more than a factor of ten *less* than the 10-meter Keck telescope currently being built on Mauna Kea in Hawaii. The SST therefore qualifies as a "poor man's telescope" in the best tradition of Russell W. Porter.

Seeking More Light

For years astronomers have sought a large-aperture spectroscopic instrument. Ramsey and Weedman decided to do something about it. Weedman's research interest centers on quasars. By obtaining many more accurate redshifts, he hopes to derive a clearer picture of their three-dimensional distribution in the universe. Ramsey is surveying stars within our own Milky Way galaxy for evidence of solar-like cycles (chiefly spots or flares) and more rapid oscillations. The large number of faint stars reached by the SST should answer many questions.

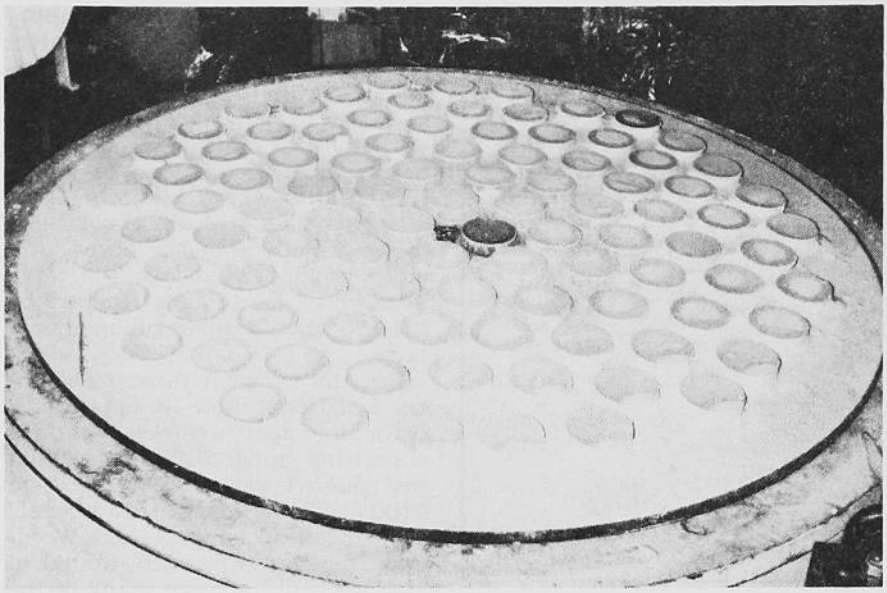
But the problem these researchers faced was, how to construct a new, large-aperture telescope on a shoestring budget? "We knew that we couldn't raise $50 million to $100 million for a 'traditional,' eight-meter telescope," said Weedman, "and so we looked around at how we could achieve many of the same results at much lower cost."

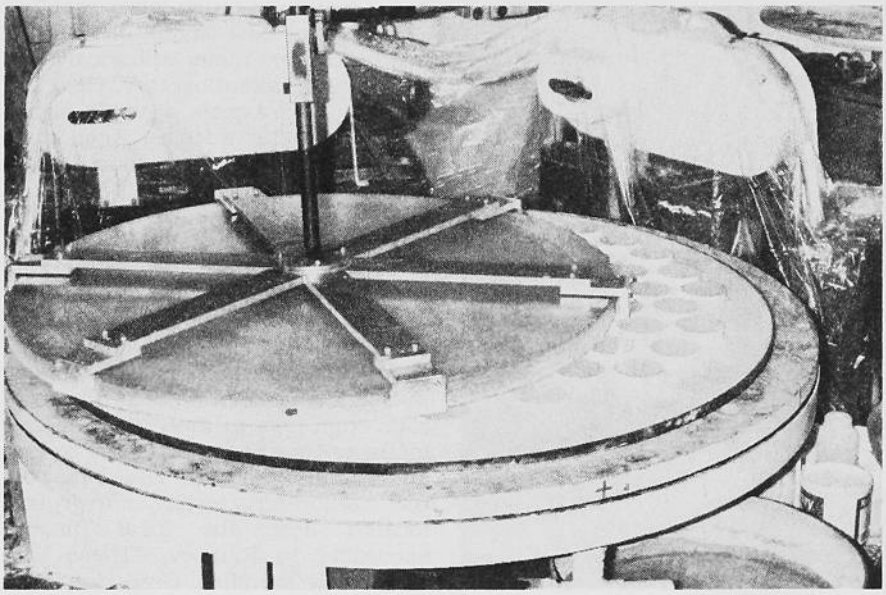
The major cost-savers of the SST are its 85 one-meter spherical mirrors which, taken together, yield the same light grasp as a single eight-meter diameter surface. Each mirror element will have a focal length of thirteen meters. The 85 mirror will work together as a gigantic spherical light collector.

As every telescope maker knows, however, a spherical mirror does not form a perfect image of a star. The resulting splash of light becomes enlarged by spherical aberration – the failure of the mirror's edge rays to meet at the same focus as those from its inner zones. To correct this, "the telescope will use a secondary/tertiary mirror pair located near the focal plane," according to Ramsey. "These will act like a modified Gregorian and correct the spherical aberration of the primary."

The figures on the secondary and tertiary mirrors are not conic sections, but must be described by polynomial expressions. These complex and strongly deformed curves will be diamond-turned into the glass. With its corrective optics, the SST's usable field of view is about 2 arcminutes. A small CCD camera will be mounted in the focal plane to assist astronomers who are using the giant telescope in finding its objects.

The secondary's diameter will be twelve inches and the tertiary's eight. Both mirrors will have perforated, concave surfaces; after these reflections, the light falls onto the end of a long fiber-optic cable and is piped into the spectrograph room underneath the telescope.





The grinding tool is faced with 3-inch diameter, 1-inch thick Pyrex disks. The two-arm machine works a face-down 1-meter spherical mirror.

Producing Spherical Mirrors

The simplicity and economy of the SST design rest upon mass-production of eighty-five identical mirrors. Spherical surfaces are much easier to make than off-axis sections of a paraboloid, as with the Keck Telescope. As a result, the Penn State team can employ a far simpler technology to manufacture them. They first refurbished a two-arm grinding/polishing machine and with it have begun their optical work. Robert Smith, an undergraduate physics major, is currently the mirror-laboratory supervisor. On the day of my visit, I was graciously shown all stages of the current operation, from fine grinding procedures to the testing of a mirror's curvature.

The two-inch thick Pyrex mirror blanks weigh 180 pounds. But before being brought into the shop, they are fine annealed, their approximate curves are rough-cut with a diamond generator and the backs are ground flat. This initial forming of blanks has been done at Glass Fab, Inc. of Rochester, NY. All blanks are worked face down on the grinding machine to prevent astigmatism – a technique which so far has proven successful.

The disks are also free to rotate on top, being driven at their centers by a large pin. Three one-horse power motors independently control the two arms of the machine and rotate the grinding tool. The complex motion imparted to the upper disk effectively randomizes any unwanted pattern in the cycle. The longer arm of the machine is adjustable for length of stroke. One-third diameter strokes with some side overhang are used.

In September of 1988, a new channeled grinding tool, slightly larger in diameter than the mirrors, was constructed. This tool should last through the majority of optical surfaces produced. It consists of 98 three-inch diameter, one-inch thick Pyrex disks cemented to a steel plate whose surface was milled to the radius of curvature. (The one-meter mirrors have a sagitta of only 4.8mm.) This new tool was then brought into shape with #100 grit, using a slightly smaller hexagonal blank.

The fine-grinding process begins when each mirror disk is worked over the tool with #220 grit to remove the diamond-cutting marks. About .010 inch of glass is removed in this process. Then the blanks are given successive spells with 25-, 12- and 5-micron aluminum oxide abrasives. Under good conditions, about five hours of grinding are necessary with each abrasive stage. The seven initial blanks received identical treatment on the machine. An extensive log book helped to establish the optimized procedures now used.

Testing the Curve

The tolerance on radius of curvature is ±1mm, or 1 part in 26,000 for a radius of 26 meters. This corresponds to a surface deviation of less than one-quarter wave. To measure (and achieve) this high degree of accuracy repeatedly, Ramsey and Weedman have constructed a rigid, T-shaped device called a profilometer to analyze mirror curvature. It consists of seven digitally-encoded sensors which act like a large spherometer. Readouts from these sensors are fed directly into a computer, which then calculates the spherical surface of best fit through the data points. This process takes only a few minutes to accomplish.

Individual sensors are capable of 100 nanometer (0.1 micron) precision – much smaller than a wavelength of light! The overall accuracy of the device, in terms of the average surface measured, is in practice a few tenths of a micron. For comparison to the mirrors being

Bob Smith records data from a profilometer resting on the surface of a fine-ground mirror. The profilometer is calibrated on a master mirror.

worked, a full-size master mirror has been ground, polished and figured. This serves as a constant check on both the profilometer and all subsequent optical surfaces.

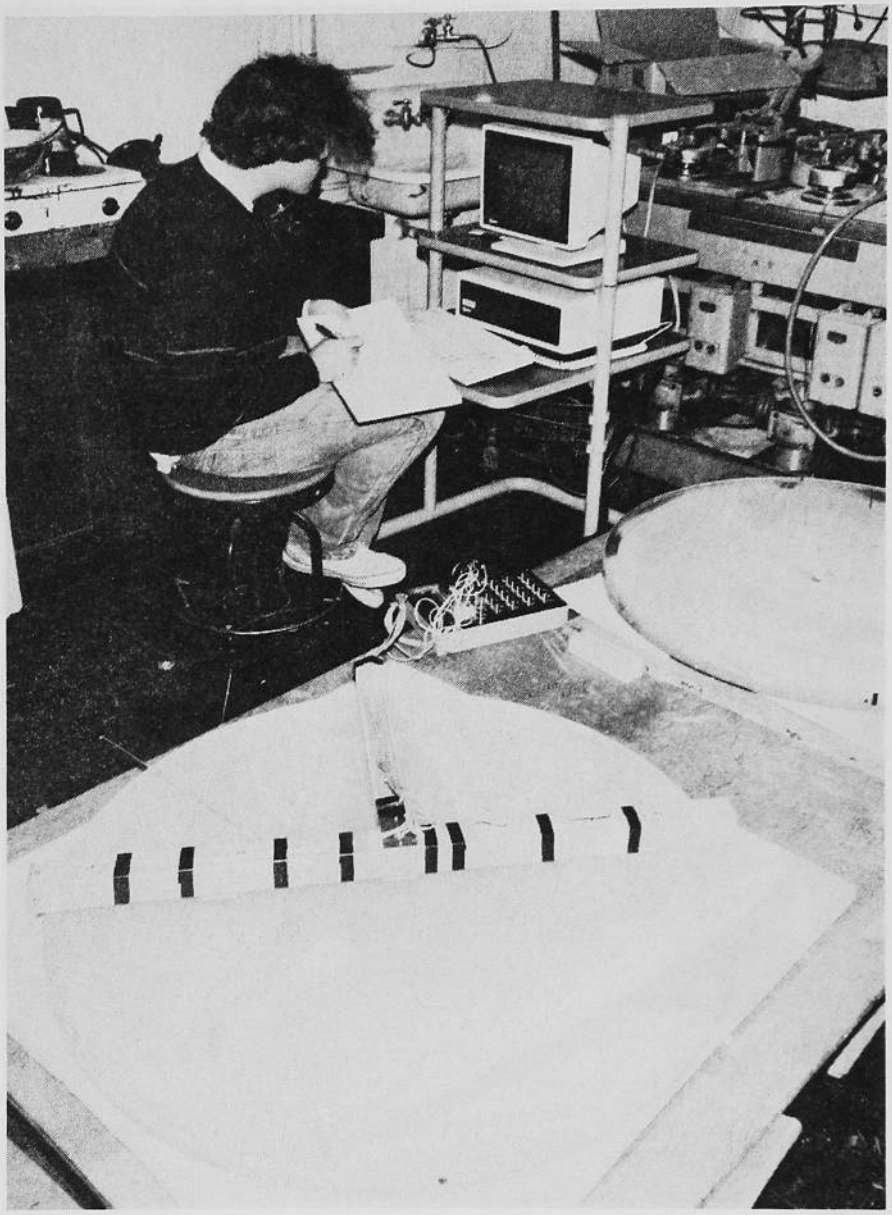
An interesting side-light to this procedure is how the mirror blanks are handled. An eight-inch diameter suction cup is placed onto the back of the blank, somewhat offset from center. The blank is then hoisted by a chain-driven pulley, which itself rides along a steel track attached to the ceiling. In moving it, the optician slides the blank off the tool and partially supports its weight from the other side. It is then brought down to the floor and tipped on edge for cleaning. The suction cup is next transferred to the ground side, the blank is again lifted and then lowered face up onto a thickly padded support for measurement. This practice would be the envy of many a TM, for it permits a single person to work a 180-pound, forty-inch diameter mirror alone.

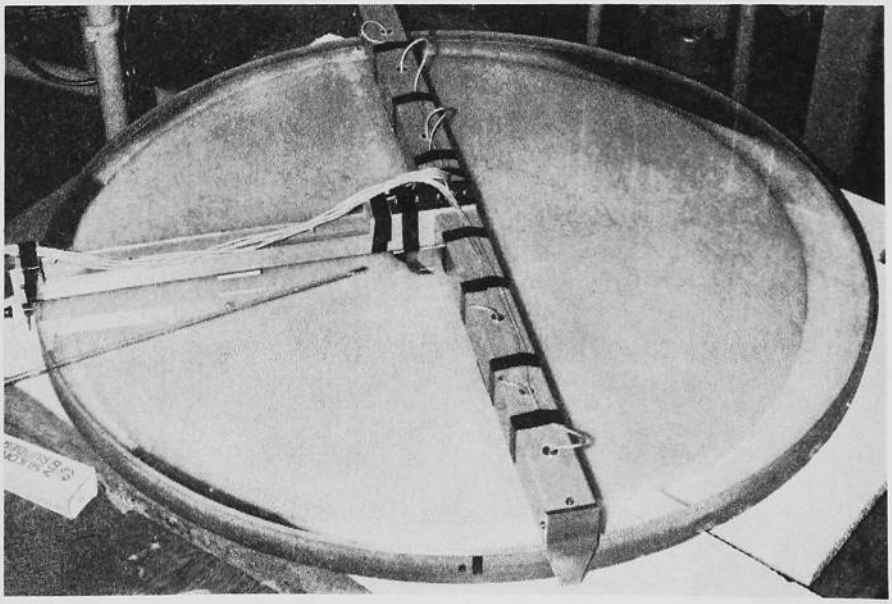
When I visited, Smith was grinding, and polishing would not be done again for many weeks. But I examined the pitch lap which had polished several preliminary mirrors. Individual pitch squares are about two inches on a side. To prevent shortening of the radii in the central zones, the lap was made slightly larger in diameter than the mirrors. It usually takes the opticians around twenty hours to polish each surface.

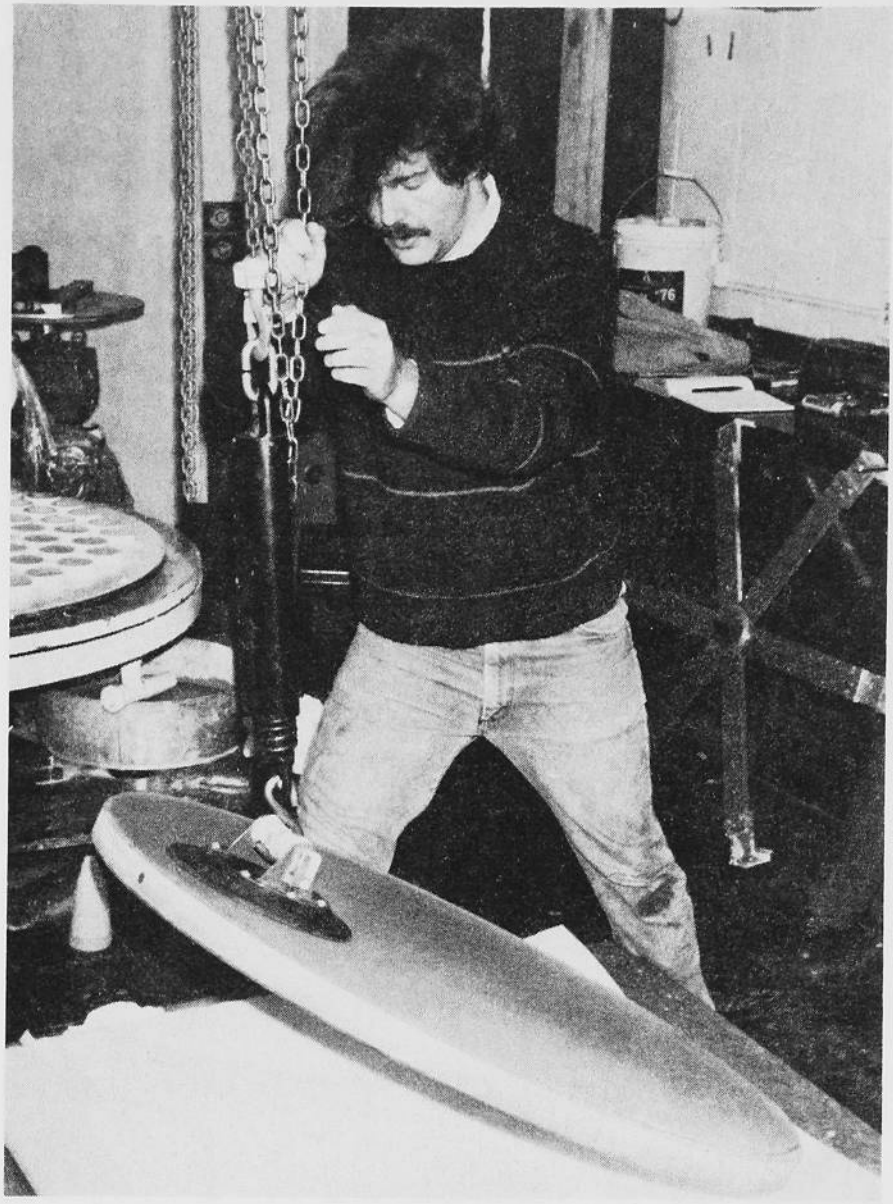
In order to check the mirror's figure after polishing, a very large testing chamber is needed. Fortunately, one exists on the same floor as the optical shop, a vacuum tunnel previously used for vacuum-infrared spectroscopic research. Set on massive brick and concrete piers, the 90-foot-long tunnel accepts a mirror, in a supporting framework, at one end. The mirror's figure is then examined with a fiber-optic-illuminated Foucault test device and CCD camera placed at the radius of curvature. After optical testing, any mirror zones that had not been revealed by the profilometer can be reworked.

Mirror Support Truss

On the fourth floor of Davey Laboratory, I inspected the working prototype of the mirror support



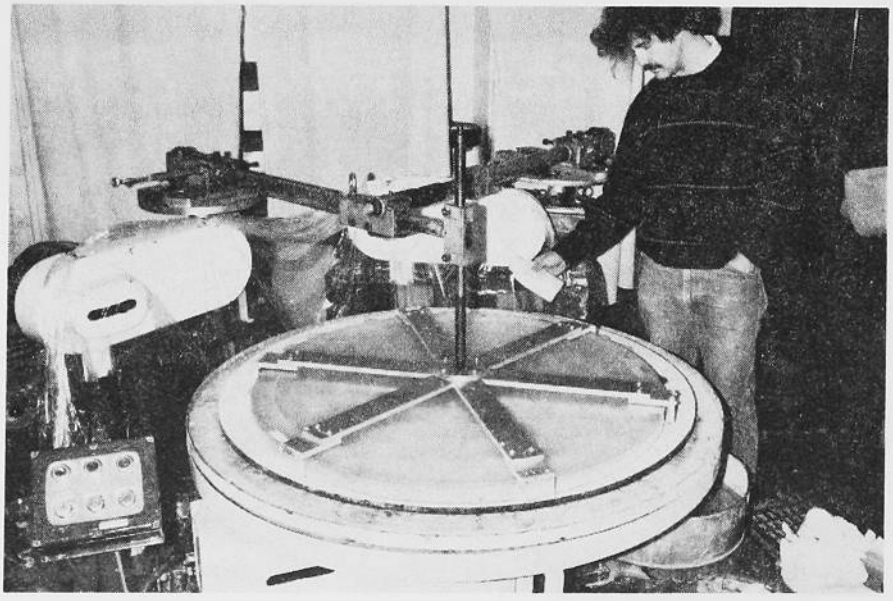




Smith handles a 180-pound blank with the aid of an overhead crane and suction cup. During fine grinding, he applies abrasive and water.

truss. This framework was designed and constructed at the University of Texas in Austin to provide the structure necessary for testing the original seven mirrors under simulated observing conditions. Each mirror is supported on an open aluminum ring which contains a precise twelve-point suspension system. The composition of the truss was chosen on the basis of its desired thermal properties. A carefully dimensioned combination of Invar and stainless steel was selected to match the coefficient of thermal expansion of Pyrex glass. This prevents unwanted changes in alignment of the mirrors during temperature fluctuations.

The critical tests of this one-twelfth-scale assembly have been carried out at Penn State's Black Moshannon Observatory with evident success. The support truss is also mounted thirty degrees from the horizontal, as in the SST design. A temporary structure near the focal plane allows testing of the superimposed star images. This ongoing inspection has not turned up any major mechanical or optical flaws that need to be corrected. The diffraction pattern produced by the multiple-mirror arrangement is just that of single, one-meter mirrors added together, and not that of a large single mirror surface.



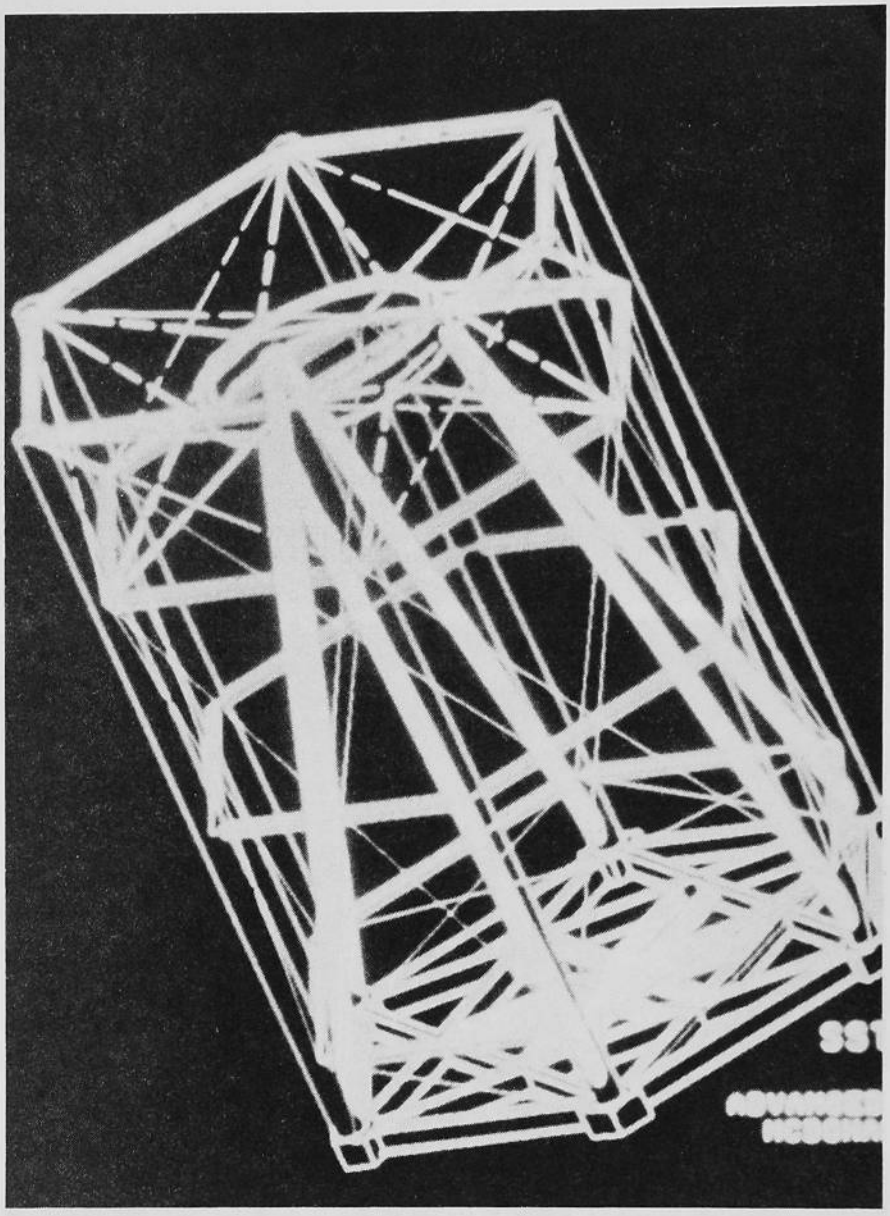
Telescope and Observatory

The telescope tube was originally planned as a simple Serrurier truss composed of four interlocking triangular sides. However, studies carried out in 1988 indicated the need for greater rigidity. Recently, Frank Ray's design team at the University of Texas has substantially strengthened the tube against vibration.

The Penn State astronomers had also hoped to get by with a simple solution to an observatory – a pair of concentrically-mounted grain-storage bins. This they abandoned in favor of a roll-off roof structure that allows rapid thermalization. This building, designed by the Texas team, will be shaped like a large funnel. Capped with a biparting octagonal shutter, it will be one of the oddest-looking observatories ever built.

According to Ramsey, fundraising efforts for the Spectroscopic Survey

The SST's tube, designed by Frank Ray, will point 85 one-meter mirrors at the sky. A seven-mirror truss will allow testing of the support system.



Telescope are progressing well. At the present pace, first light with partially completed optics and instrument is expected at the McDonald Observatory site by 1993. Mirrors will be added as they are finished, gradually raising the light grasp of the telescope to its full potential. Then, the SST will begin to survey the heavens as the most powerful spectroscopic "eye" ever created by human ingenuity.

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Acknowledgments

I wish to express my deep appreciation to Drs. Ramsey and Weedman, and to Robert Smith, for kindly allowing me to inspect and photograph the construction of the SST. In addition, they have patiently answered my many questions, aided in securing some of the newest illustrations, critically read the entire manuscript for accuracy, and finally gave their permission for its publication. All of this, I hope, has resulted in a truer picture of this revolutionary telescope.

TM readers who would like to contribute to this project may contact Dr. Lawrence Ramsey or Dr. Daniel Weedman at this address:

525 Davey Laboratory
The Pennsylvania State University
University Park, PA 16802

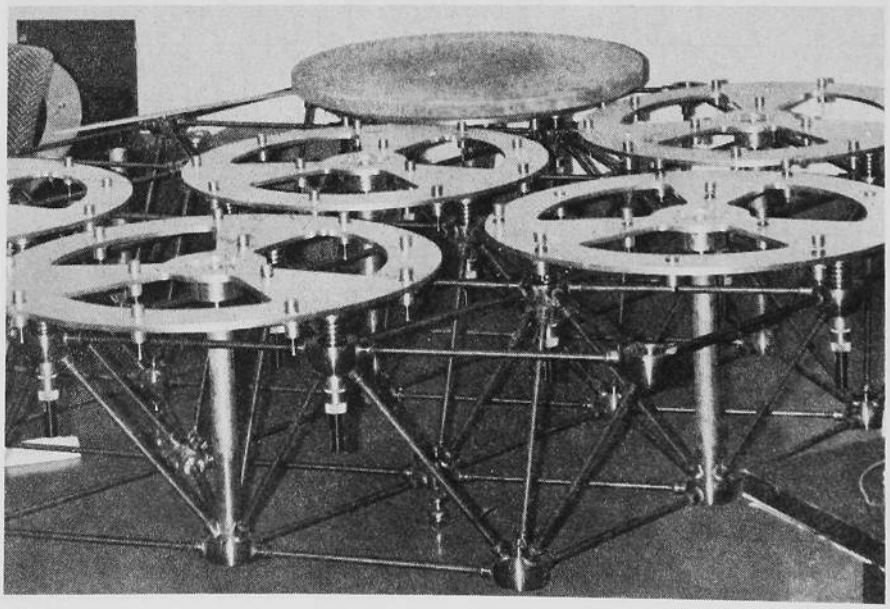
Additional material on the SST and the history of its design is found is the following sources:

"Seventy-three Spectroscopic Eyes on the Stars," Nan Crystal Arens, Research/Penn State, vol. 8, no. 4 (December, 1987), pp. 20-22.

"New Giant Telescope for Spectroscopy," (unsigned), S&T, vol. 75, no. 2 (February, 1988), p. 129.

"The New Eye of Texas Is Soon to Be Upon Us," M. Mitchell Waldrop, Science, vol. 239 (February 19, 1988), p. 868.

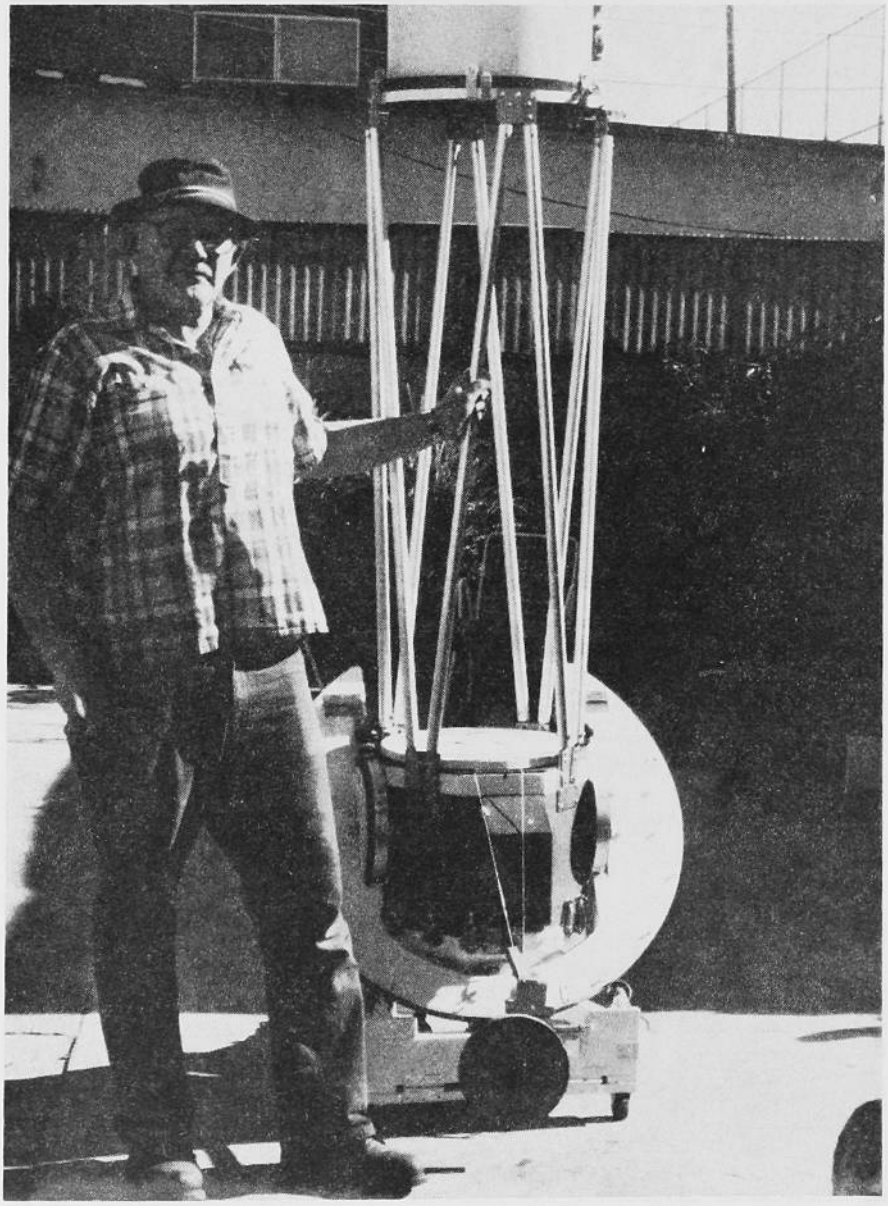
""Putting More Light on the Subject," (unsigned), Compressed Air Magazine, November, 1988, pp. 8-13.



A Split-Ring Mounting with that Dobsonian Feel

I have long admired the Kitt Peak 4-meter telescope. There's something about its look, I guess. Anyway I decided that if I ever built an equatorial mount, it would be of split-ring design.

Then when I read Joe Pearson's article in *TM#27* about his beautiful lightweight, portable split-ring scope, and later a photo layout in *TM#31* on Gary Walker's superb ultra-light split-ring, I started having ideas. Although my scope differs from theirs in significant ways, I want to acknowledge the debt I owe to these articles and their authors. They were a gold mine of ideas and good advice.



David Moerke's 12.5-inch f/6 split-ring mount offers Dob-like compactness and equatorial convenience. For viewing ease, the upper end rotates.

My 12.5-inch f/6 scope is a combination of a Porter split-ring and Dobsonian. While definitely a split-ring, this scope has so many Dobsonian features that it could almost be called a Porter-Dobsonian, or more accurately a Newtonian-Porter-Dobsonian design. And let's not forget the guy that designed the truss — Mark Serrurier.

Folding Counterweights Because of its length, and to withstand the stress of a rotating upper end, I designed the tube somewhat heavier than usual. This conflicts sharply with the necessity of keeping the mount small enough to fit through a 28-inch-wide doorway that leads to its storage area.

To reconcile these conflicting demands, I turned the split-ring on its side, hinged 3.5 inches of the ring tips, and held the diameter of the ring to 32 inches. However, it was impossible to balance so long a tube in so compact a polar ring. The tailgate was unable to carry the required weight. Thus I decide to design a system of weights to balance the tube.

Extendable weights are nothing new; they have been used on many types of telescope mounts. I developed mine by the old-fashioned process of trial and error. There are

two fold-out counterweights, one on the top and one on the bottom rear of the lower tube. Each weight has two positions. At some angle positions, I use 0.040-inch nylon line to supplement the mechanical arm support. The telescope also requires a detachable weight supplied, in this case, by an old grinding wheel.

I used odds and ends of steel for the weights, but lead would have been more compact. As can be seen in the photos, at some altitudes, the closed counterweight is sometimes on the opposite side of the center of gravity and must be balanced with the detachable weight.

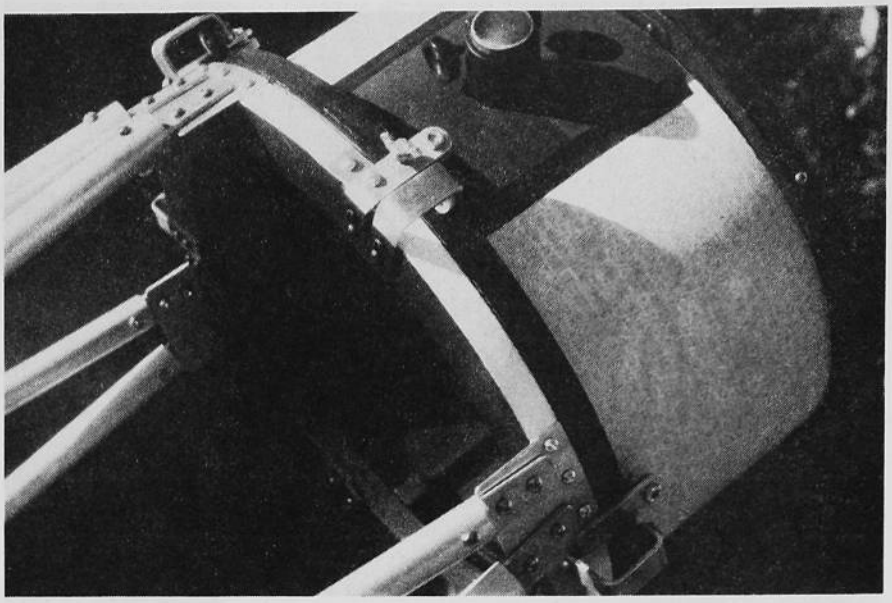
It takes about 30 seconds to fold out, close up or change the angle of one of these counterweights. Roughly 90 seconds is required to switch from one to the other. With no brakes applied to either axis and with one of the counterweights extended and the detachable weight in place, the scope is usually in balance.

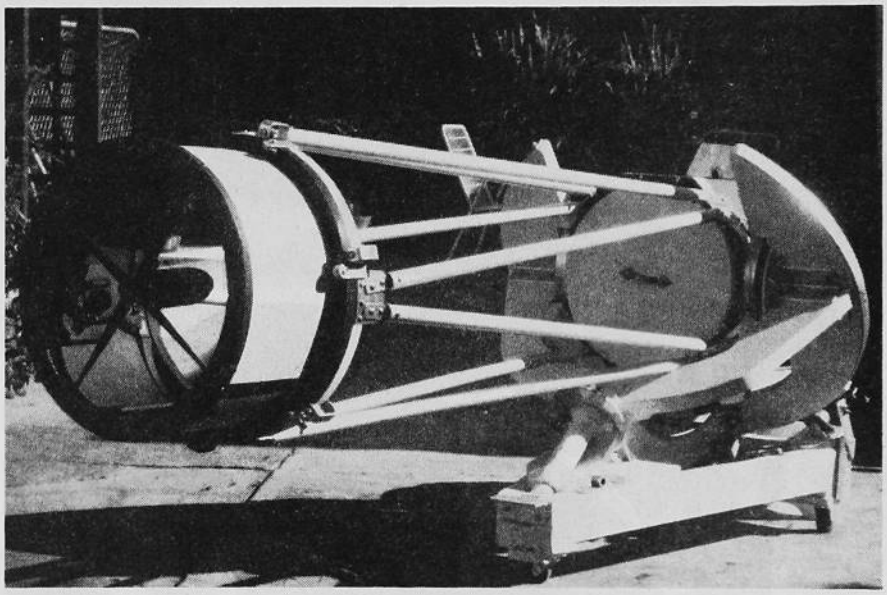
After seeing how well the folding weights work on my telescope, I suspect others will find similar counterweights useful on long and heavy tubes, and for balancing rotating upper ends, photo equipment, guide scopes, and the like.

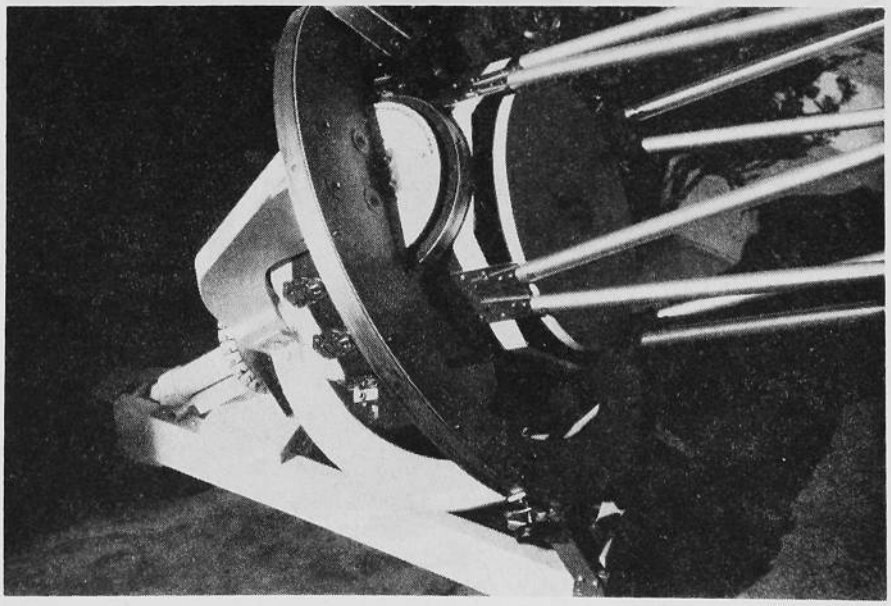
Brakes For the minor imbalances that remain, Teflon brakes augment the counterweight system. The brake mounts are steel with thin flexible stainless steel pressure plate to which the Teflon pads are attached. I occasionally use them to lock on to an object, but most of the time they serve to hold the tube steady for transport and storage. Usually only one brake is needed, but for easier access I mounted two. Because the RA split ring rides on steel casters, it moves a bit too freely, so a slight pressure is usually applied with the Teflon RA brake. This gives a very close approximation of the feel of a Dobsonian.

Rotating Upper End This rotating upper end is a drum built of two 1.75-inch-wide and 0.75-inch-thick plywood rings separated by nine 0.5-inch diameter, 8-inch-long wood dowels with a thin Formica wrapper and a half-inch-thick focuser board.

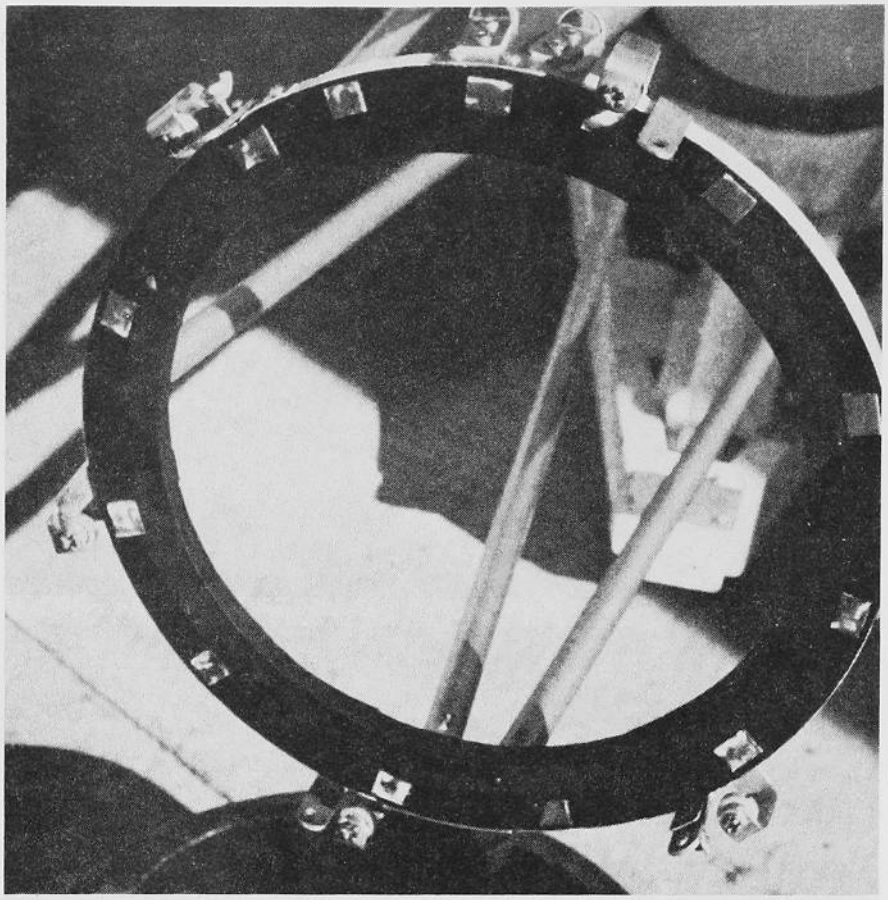
The 1.25-inch focuser is from University Optics. To ensure align-

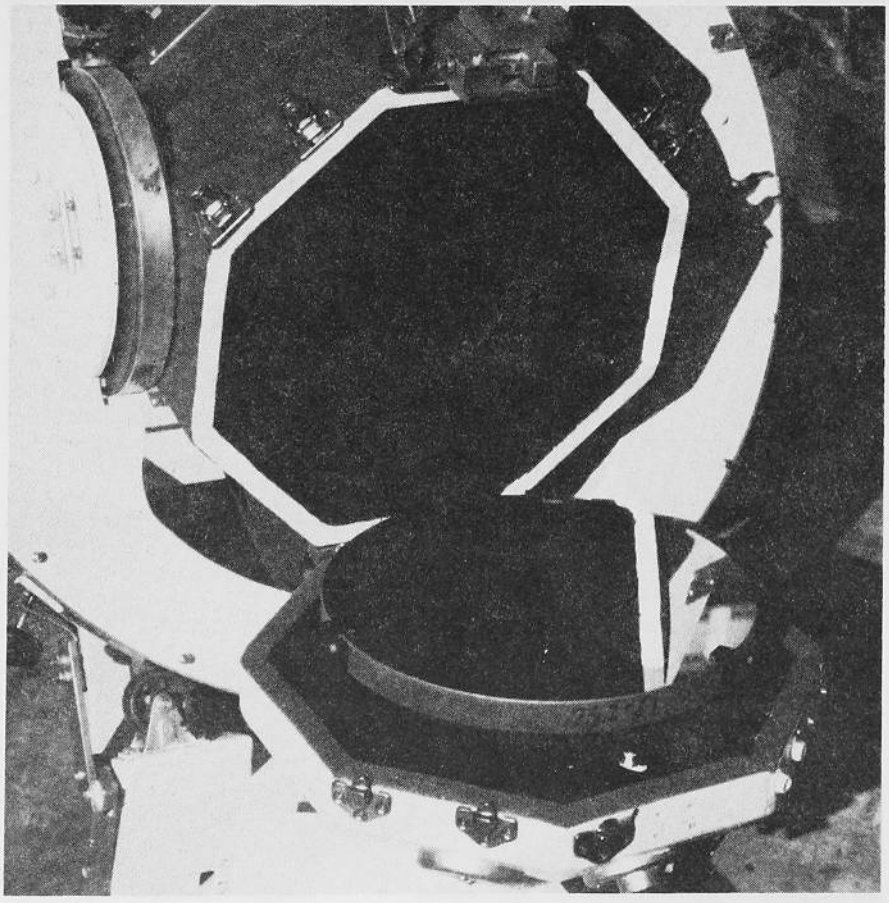






In close-up, the brackets and rollers of the upper end are visible. Side view reveals the classic Porter split-ring yoke. Note the folding ring tips.





ment, the holes for the dowels were pilot drilled with both rings clamped together, then separated and counterbored each hole to a 3/8-inch depth and 1/2-inch diameter. The focuser board and both rings are scalloped out for lightness.

The bottom ring of the drum has Formica on the top and bottom bearing surfaces. The drum rides on thin Teflon pads attached to the formica top surface of the 3/4-inch plywood top ring of the Serrurier truss. To the bottom Formica surface are attached twelve roller brackets. These assemblies capture the upper drum while allowing it to rotate freely on the Teflon pads. The Formica on this ring provides strength and a flat surface for bearing.

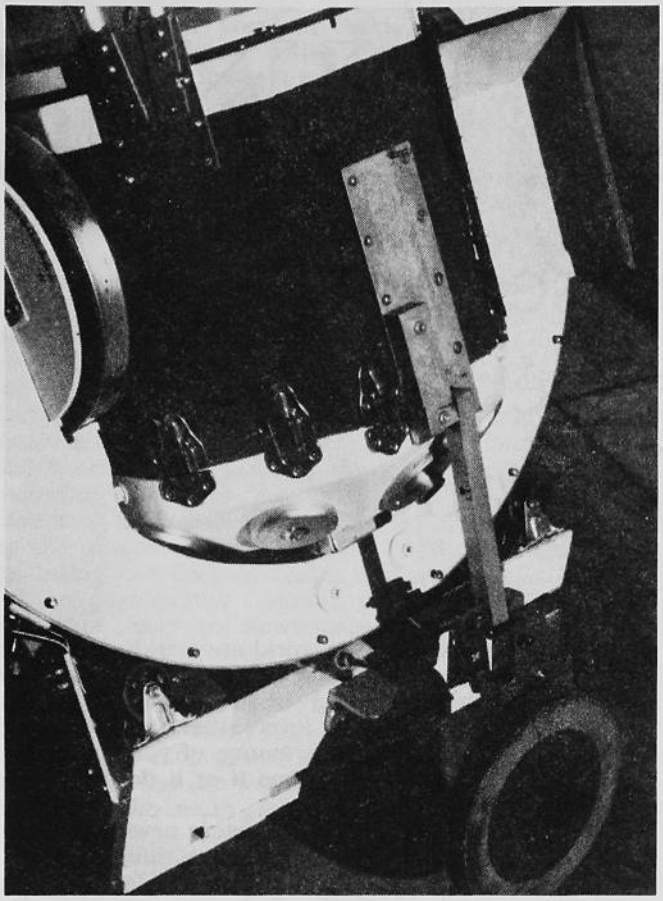
The roller assemblies consist of hand-formed 0.090x1" aluminum brackets, and 7/8-inch diameter sliding door rollers with ball bearings. Two aluminum brakes are placed on opposite sides of the ring. This rotating drum works very well and gets constant use.

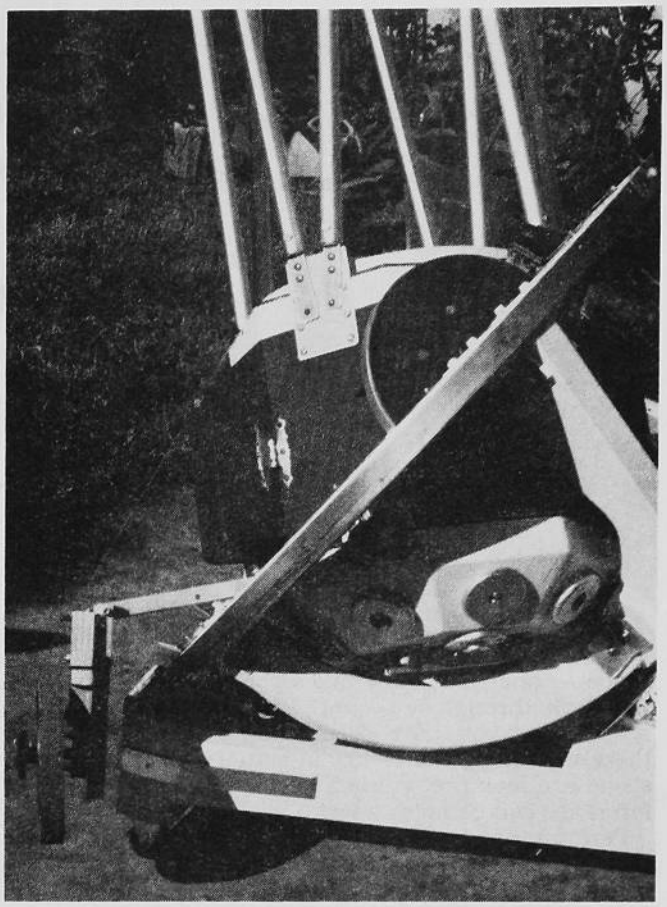
Because this scope is for visual use only, I used a 2.140-inch diagonal. The spider and diagonal holder are from Kenneth Novak and Co., and the diagonal mirror is from Coulter Optical.

Serrurier Truss The diameter of the top ring is 17.5 inches OD and 14.5 inches ID. The top tube mounting plates are 0.064-inch aluminum. The struts are 1 inch OD by 0.055-inch-wall aluminum tube with 0.125-inch thick aluminum mounting plates at the bottom. I am very pleased with this truss; it is extremely steady. Because this is strictly a backyard scope and strength was my main concern, I bolted the truss together. The octagonal tube has plenty of room for a quick disconnect system if I later decide to add one.

Lower Tube and Tailgate The lower tube is made of 3/4-inch plywood. Not apparent in the photos are octagonal rings at both ends, added for strength. The declination bearings are 10-inch diameter 1.25-inch (1" + 1/4") plywood with Formica sides. The wrapper band is 1.00 x 0.060" aluminum strap. The lower tube is 16 inches wide, excluding the trunions. The combined length of the lower tube and

Looking a bit deeper, we see the pads and rollers that secure the upper end. The contoured tailgate folds down to reveal the primary.





Folding counterweights add weight where it's needed to keep the tube in balance. Note very small clearances between the tube and mounting.

tailgate is 17 inches.

The tailgate is 3/4-inch plywood. It consists of two octagonal rings at the top and eight tapered wedges and a small backboard. Access for collimation is through three 1.5-inch diameter holes. The hole plugs are 35mm film container caps with dowel handles. The collimation tool is a modified file handle.

Both the lower tube and the tailgate were made from full scale drawings, as was the whole scope. I made preliminary drawings at one-third scale. During assembly, simple wood fixtures were used to hold parts in position and at correct angles. Screws, nails and wood glue were used to fasten parts together. Wood putty was used as required. Various fixed weights are placed around the back of the tailgate.

The 12.5-inch primary mirror from Coulter is mounted in a nine-point flotation cell from Kenneth Novak & Co. The total length of the tube assembly is 76.5 inches. From the pivot point at the center of the dec bearing to the bottom of the tube is 12 inches. To the top end, the tube measures 64.5 inches.

Polar Split-Ring Assembly The horseshoe or split-ring is 32 inches in diameter and is made of doubled-up 3/4-inch plywood. So are the south yoke and bottom brace. The aluminum wrapper is 1.25" x 0.125" aluminum strap. The bottom brace gives extra strength to an already strong mount by keeping the yoke and ring from spreading apart under the weight of the tube assembly when the scope is pointed near the zenith. This adds some weight, but this was easy to balance with the counterweights. The narrowest point at the bottom of the ring and yoke is 3.38 inches.

I joined all connecting points with aluminum angle and steel bolts. The narrowest point on the brace is where it clears the motor; it is 2.75 inches wide at that point.

The Base The base is built mostly from 2x4s and 3/4-inch plywood. To allow more room for deployment of the south counterweight, a shorter south end would have been preferable, but I used a rather lengthy 9-inch arbor for the south bearing. This has made for a long but surprisingly stable base. I held the north end of the base to 20 inches for balance considerations. The north-south length of the base is 34 inches. The polar split-ring rides on 2-inch by 7/8-inch steel casters.

The mount has a very simple clock drive. Because I use the drive only to follow the Moon and planets while I am sketching, all I require is 20 to 30 minutes tracking. Power is supplied by an old 2.5 RPM electric motor. I simply attach a length of 0.040-inch Nylon line to one of the screws spaced around the edge of the split-ring. This simple method works okay for the necessary time.

Building this telescope was a challenge for me, as well as a cram course in the equatorial mount because I'm still fairly new to astronomy. One side benefit of the split-ring mount that I like is that it makes visualizing the celestial equator easy.

In operation I have found the split-ring mount exceptionally stable, with smooth operation and great load capacity. Like my Dobsonians, this telescope was a pleasure to build and is a joy to use.

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SUPERTUNE

Your Telescope for the Very Best Performance

What makes the difference between a really fine telescope — one that really takes your breath away when you look through it — and the hundreds of average scopes that you have seen before? To tell the truth, there's not much difference in actual construction. One scope can look pretty much like any other, but the performance can be miles apart.

Performance is one of the buzzwords that has been making the rounds for the last several years. When Richard Berry visited the 1989 Winter Star Party last February, he reported in *TM#36* that some large aperture telescopes he used there were working to the diffraction limit. Does your telescope perform as well? As the builder of these 18-inch to 25-inch telescopes, I'd like to point out some of the details that I believe make a telescope deliver all that it's capable of.

But let me first give credit where credit is due. In *TM#23*, Gregory Reeve wrote "The Ultimate Newtonian." This article is inspiring and well worth reading. In *TM#31*, I read "Optical Experts Comment on the TSP." However, gentlemen, this is 1989. You must acknowledge that high performance is not limited to 6-inch and 8-inch scopes. Nor, for that matter, is it confined to 10-inch or 12-inch scopes.

And that is the point of this article. Telescopes, both small and large, should perform to the theoretical limits of their ability. You need not accept second-rate performance from a telescope, whether that's how it was when you first built it, or that how it came from the manufacturer.

Usability is another important feature of a fine telescope. Is your telescope pleasant to use? Do the optics make you hate planets — or love them? Is your light grasp enough to show you all that you want to see in deep sky objects? Is setup quick and painless, or a dreaded undertaking? Does the mounting provide a solid, steady image, or does the mount hula through the night?

Portability is another "in" feature. Where there is light pollution, there is a need to move telescopes. There are now amateurs hauling 30-inch telescopes around the country to star parties. More on this later.

Dream Telescopes Let's now see if we can see if we can make your dream telescope more useable, and perhaps up the performance a little. Because 95 percent of the telescope makers in the world are working with the Newtonian design, this is what we will concentrate on.

But first, there is one subject that must be addressed. For you refractor lovers, there only so much we can do to help the performance of you telescope. After all, the objective either has it or it doesn't. Let's slaughter the sacred cows.

The first sacred cow is that refractors never need collimation. Right? Sorry! There is no such thing as a perfect objective cell, and it is almost always a fact that the machining is never perfectly square or concentric. To rely on the fact the tube is cut off perfectly square is ridiculous. Even a few thousandths of an inch makes a difference in some lens designs. After all, the lens makers works to tolerances of a few millionths of an inch when making the objective. One one-thousandth of an inch is a thousand times that amount. A super-accurate tube cut is probably not closer that .002 or .003 of an inch to being square. Use a Cheshire eyepiece every once in a while and check it. You will be surprised at what you find.

Almost never will you find a telescope that is moved from place to place that is in perfect collimation. Collimating your refractor is so simple that you will kick yourself for not doing it before. If you are wondering if it really makes a difference, try it. And be assured that you will easily see the difference.

First, put the lens cap on the front of the objective, then put the Cheshire directly into the focuser, not the star diagonal. As you look into the Cheshire, you will see two rings of light that look like doughnuts. Simply adjust the screws on the objective cell until the two doughnuts become one. That's it, you're done.

Please note that this is optical collimation, not anything mechanical. DO NOT use the method described in *S&T*, April 1988, page 365. The *S&T* method depends on how accurately you make the cardboard mask. The Cheshire eyepiece method of collimating relies on the reflection of light from the front and back of the objective, with nothing artificial. It really works.

After the scope is collimated straight through, put the Cheshire into the diagonal and check it again. Surprise! If your diagonal isn't adjustable, perhaps the metal back is thick enough so that you can add three setscrews to it to use for fine tuning the alignment of

the diagonal. If you can add collimation screws, remount the diagonal with silicon cement. If not, perhaps you could make a new back without too much trouble.

Portable Set-Ups Are all your friends are tired of hearing that it's too much work to set up your scope? Is getting out your giant "portable" pier for a quick observing session just too much hassle? By the time you set up the pier and mount, has the planet has set or gone behind a cloud?

What about a *second* mounting for your telescope? An easy mounting to set up? How about building a simple Dobsonian mount that would take less than a minute to set up. Dobsonian mounts can be built for the cost of a sheet of plywood, a few scraps of Teflon and Formica, and a couple of other minor parts from the local hardware store. A good guess would be that under $50 would do the job. For ideas, see Richard Berry's mounting in *TM#21*, page 41. This is a good looking mounting for a 6-inch f/15. Or you might get an idea by the photos in *TM#34*, page 13. This is a binocular mounting, but the principal is the same.

Killer Newtonians Almost all telescopes made by amateurs today are Newtonians, because as everyone knows, that's where the maximum performance for the dollar comes from. You have probably been thinking this, hearing this, and reading this for years. *Telescope Making* has had many technical articles explaining just what causes each proton of light to do what. But most of these articles are way over my head. They just don't help guys like me to get the telescope to work any better.

So — you just want to make the darn thing work, and work like it did in your daydreams! Let's examine some telescope design criteria and go over each step in telescope design one step at a time.

Use the Best Materials Let's talk about commercial telescopes for a moment, because the manufactures face the same problems amateur Telescope makers face when building a telescope. One would get the impression from reading all the ads that telescopes are sold strictly on a price basis. Because it's impossible to make a $5,000 telescope and sell it for $1,695, something has to go. Usually it's the quality of the components.

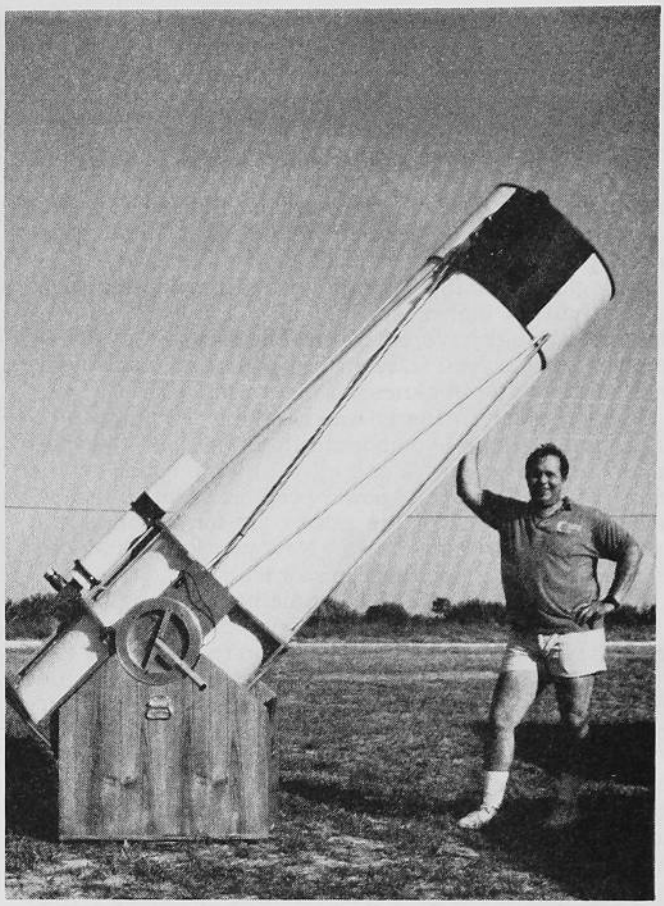
How many commercial telescopes are on the market, that work perfectly, have super solid mountings, have great optics, and are reasonably priced? What happens when every part of a telescope is made properly? Usually the telescope is priced right out of the market. Is this the reason that we telescope makers build our own telescopes?

So — what does this have to do with Telescope makers building their own? Everything! Telescope makers don't have to pay for expensive labor. *Ergo*, we can afford to pay for top-quality components, and rest assured that the important part of our telescopes will work properly.

This is a hard lesson to learn. Most of the time we're first tempted by the "bargain." After finding out the true price of the bargain, we get smart and buy the quality we should have purchased in the first place.

This makes good quality items cost more because we purchase so many things twice. Paying for top quality the first time around doesn't cost more after all.

Don't Skimp on Optics You have probably heard so many times that you get what you pay for you are probably tired of hearing it. Sometimes it's true and sometimes it's not. Sometimes a mediocre optical house



Tom Clark stands beside a 250-pound 25-inch f/5 telescope. The optics alone weigh 76 pounds. The apparently solid tube is made of thin sheet styorofoam; John Dobson nicknamed a similar telescope "the coffee cup."

turns out a great mirror. Sometimes a manufacture with a flawless reputation for great mirrors and good prices lets a lemon slip out the door.

If you have a mirror that is no good, don't despair. Refiguring costs much less than a new mirror. Just make sure that you use an optician who can be trusted.

Everyone agrees that it's time to give a bad reputation to bad mirror makers. But — are you sure that the mirror is bad? Perhaps your local club expert will check it for you. If your club doesn't have such a person, take it to a star party. There will almost certainly be some one there who is able to help you decide if the mirror is bad.

Mirror Cells There is only one way to mount a good primary mirror, and that's in a properly constructed mirror cell. Where can you buy such a cell? You can't. However, you can modify a good mirror cell to make it work better. If you have the capability you can always make your own. *TM#26* has an excellent article on flotation cell design by Dave Chandler.

Why are mirror cells so important? For the same reason that having a good mirror is important. Guess what? Take an excellent mirror and put it in a lousy cell and, presto, the mirror is now as bad as the cell.

You would think that everyone would know this, so why rehash it? Guess again. At the next star party you go to, take a look at how most Telescope makers have

their mirrors mounted. Then look at how the hot performers have their optics mounted. Hmmm.

If you have a good cell, check to see just what the mirror is resting on. If there's not a piece of cork under each resting point, remove the tiny button that is there, and glue in a piece of 1/8 inch thick cork in its place. The cork should be equal to about one square inch for each point. After all, how would you like to sleep on a bed of nails that only has 9 or 18 nails in it! What makes you think your mirror likes it any better?

While you're at it, count the pads. If your mirror is bigger than 14 inches and not on a 1:6 full-thickness blank, it should have 18 of those points — not 9. For smaller mirrors, you have to use your own judgement, depending on the thickness of the mirror.

If you wonder if this is worth taking the time to do right, here's a simple demonstration. The next time you have your scope out, focus on a star and look at the image with a fairly high-power eyepiece. Aim your dew-blaster at the back of the mirror for ten seconds and then look at the image again. Now you know just how sensitive the figure on your mirror is.

If your mirror is glued to something, it might be a good idea to replace that slab of plywood or aluminum or whatever with a proper cell. If you're convinced that this method of mounting a mirror works, fine. It's just that we have seen several miraculous cures to bad mirror figures just by changing from glue to flotation!

Diagonal Size The next stage in setting up a real performance scope is using the proper size diagonal mirror. For visual images, there's no need for a large diagonal; for deep-sky photography, you need to illuminate a large field.

One thing is for sure: large diagonals are not cheaper than smaller ones. So let's figure out the right size to use.

The following is Ralph Dakin's original formula. Through an unfortunate mishap, the formula was misprinted in *Sky and Telescope* back in 1962. Although they published the correct one a month later, the often misprint formula is often quoted. Alas, one of life's little ironies.

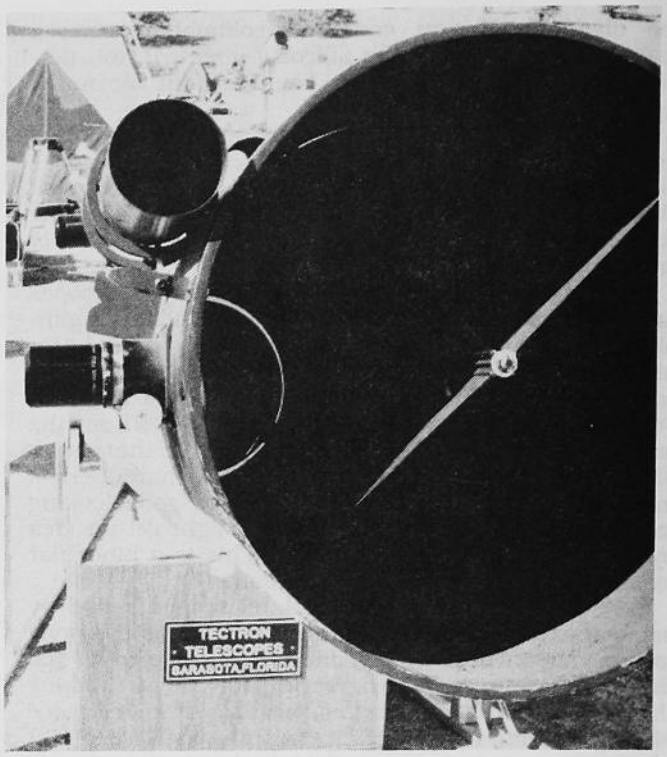
$$A = \frac{V(F-S)+C(D-V)}{2(F-S)-(D-V)} + \frac{V(F-S)+C(D-V)}{2(F-S)+(D-V)}$$

$$d = \frac{V(F-S)+C(D-V)}{4(F-S)-2(D-V)} - \frac{V(F-S)+C(D-V)}{4(F-S)+2(D-V)}$$

D= Diameter of the primary mirror
F= Focal length of primary
S= Sagitta of the mirror = D·D/16·F
C= Intercept distance, diagonal to focal plane
V= Diameter of fully illuminated field
A= Diameter of diagonal minor axis
d= offset distance for the center of the diagonal

Ralph is now happily retired and living in Maine. He has furnished me the following: For visual use, use a field diameter between 1/4 and 3/8 inch to keep the diagonal small. There is no need to offset the diagonal mirror. For prime focus photography on 35mm film the field size should be about one inch in diameter, and the diagonal should be offset to give even illumination of large diameter, fast systems.

The only thing we have changed from Mr. Dakin's advice is to use a slightly larger diameter of 100 percent illumination to one-half an inch for visual observing because 32mm and 40mm wide-angle eyepieces are



widely used nowadays. In 1962 such eyepieces weren't used.

With the aid of a programmable calculator it is easy to calculate different sizes by simply changing one of the four variables. Notice that the formula is much simpler than it looks at first glance. The term (F–S) is used four times, but only has to be figured once. The same is true for (D–V). You can also set S to zero if you wish because it is a small number and negligible for all practical purposes.

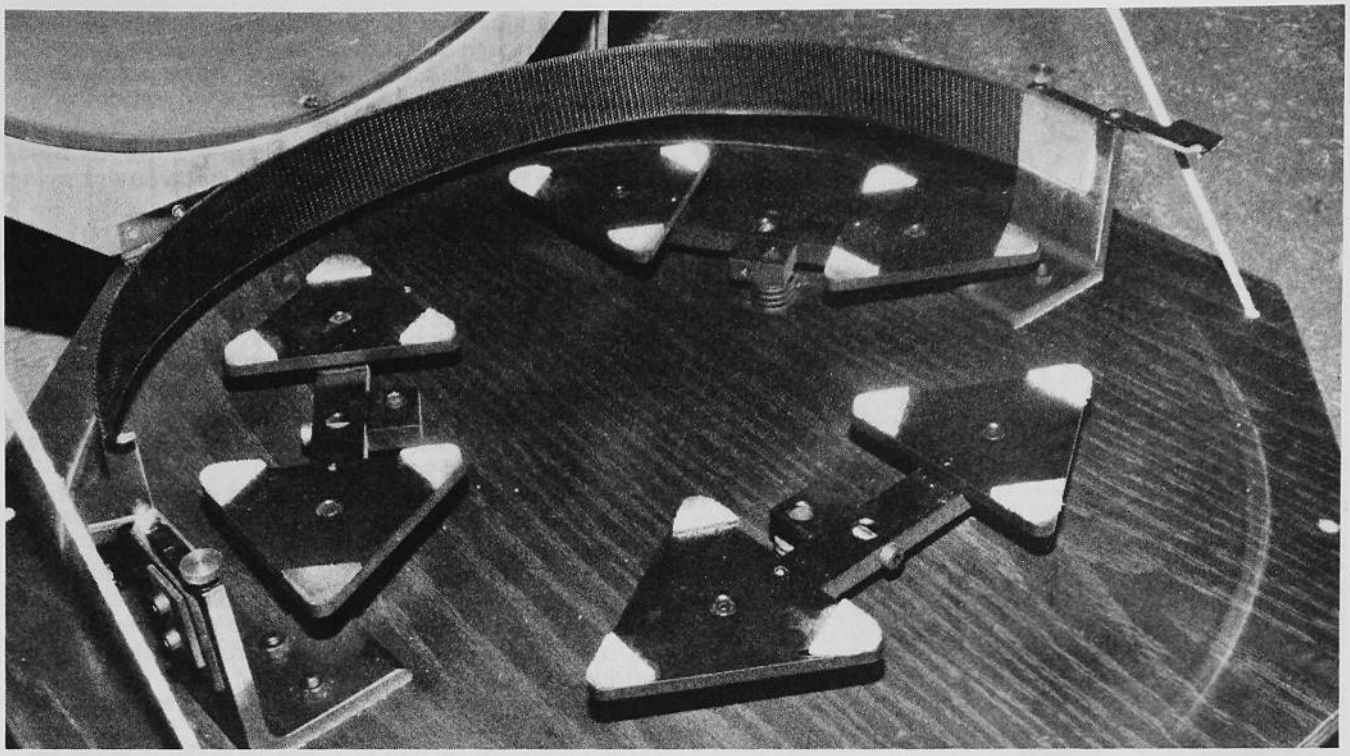
The following are samples run through a calculator, using the above formula, for mirrors that are in wide use. The sizes in parenthesis are actual diagonals that have been used in telescopes with very good results. In all cases the planetary images showed a marvelous improvement.

10-inch f/5.6 = 1.61 (1.8)
10-inch f/4.5 = 1.98 (2.1)
13-inch f/4.5 = 2.35 (2.6)
17-inch f/4.5 = 2.91 (3.1)
18-inch f/6.0 = 2.33 (2.6)
20-inch f/5.0 = 3.09 (3.1)
25-inch f/5.0 = 3.67 (4.0)

There have been many explanations, accompanied by charts and diagrams, of how light and optics work. *Telescope Making* is filled with such articles. You don't have to be an optical engineer to understand them. As a matter of fact, you don't have to understand them at all. All that matters is that the visual images show drastic improvement as the central obstruction is reduced in size. Try it!

As a final note, see "Newtonian Telescopes" by Richard Berry in *TM#9*, page 6. If you are the technical type, this compendium of Newtonian information will answer more questions than you can think of to ask.

Focuser Height When you set up a programmable calculator to check diagonal sizes, the first thing that



Care in mounting the optics is essential. At left, a Novak focuser has been cut down to 1.5 inches high. Above, the mirror cell for a 20-inch mirror has an 18-point flocation and a 2-inch-wide sling under half of the circumference.

really becomes apparent is the importance of the height of the focuser. A standard 17–inch scope would require a 2.8–inch diagonal if no focuser were used and the eyepiece were mounted flush to the tube. But if the focus is located 7 inches outside the tube, as many focusers sold in the past required, then you would have needed a 4.3–inch diagonal.

Helical focusers are available that are from 1.25 to 2 inches high above the tube. Rack and pinion focusers on the market range from 1.5 inches high to as high as you like. Using a focuser of 1.5 inches high would call for a diagonal size of 3.1 inches.

This may seem like a small variation, but it results in a decrease from a 25–percent obstruction to a 16–percent obstruction of the primary mirror. As a rule of thumb, a high–performance visual scope should use no more that 17–percent obstruction, and 10–percent obstruction allows almost refractor like performance. Although it's hard to get down to a 10–percent obstruction with anything faster than f/7, telescopes this long aren't very practical in the sizes that are in use today. Look at the back cover of *TM#13*, and you will agree! (If you happen to have an observatory, the definition of practical quickly changes.)

Collimation This buzz word has been busy as a bee for the last couple of years, in large part from my own efforts. But facts are facts: today's large, fast scopes need precision collimation much more than the small, long–focus scopes of yesteryear.

It is so easy to gain a such a large improvement in telescope performance, that you will wonder why it took you so long to learn how to do the job right. And the funniest thing is that it only takes a moment when you set up to practically nail the collimation. *Telescope Making* has carried information on collimation in *TM#9*, *TM#18*, and *TM#22*. *S&T* also carried very good articles in March and April, 1988.

A key point in collimating a Newtonian is that most of the fine adjustments in collimating your optics are done to the secondary mirror. If your secondary holder doesn't lend itself to superfine adjustments to the diagonal mirror, you might consider replacing the spider and diagonal holder. Those made by the Kenneth Novak Co. are well made and not very expensive.

Tectron Telescopes, the company I own, produces a 43–page booklet "Perspectives on Collimation." This booklet summarizes nearly everything ever written on collimation. Collimation will do as much for your telescopes performance than the best eyepieces can. Remember, eyepieces can deliver their best only if your scope is in collimation to begin with. If you don't have a set of collimation tools for your scope, perhaps someone in your club does, and will let you use them until you can get a set for yourself.

Eyepieces Here's one advertising slogan that rings true: your eyepiece is one–half of the optical system. In the last few years such drastic improvement has taken in place that older eyepieces show their age when compared to the new designs now in use. If your scope is under 12 inches aperture and slower than f/6, you won't notice as great a difference as you will with larger, faster scopes. Furthermore, the size and weight of the new eyepieces make them difficult to use in small scopes.

The best advise you can take is to look through all the new eyepieces in the type of scope you plan to use them in, before you make a purchase. No one can tell you what's best for you like you can tell yourself. A direct comparison cuts through the advertising rhetoric, and is really the only way to see what works best for you. If your club members don't have the eyepieces you wish to try, a visit to a star party will solve that problem. Try them and compare them before you buy

and you can't go wrong.

If their rather narrow 50-degree apparent field doesn't bother you, there are some great buys in so-called "Plossl" eyepieces today. Before you run out and buy a set of these, check the performance of the 65- and 82-degree apparent-field eyepieces. After you've used them, it's hard to go back to narrow fields.

Our advise is to buy top quality eyepieces to start off with. If you don't, you will just end up buying everything twice. That's okay — it makes a supply of cheap used eyepieces for the beginners in our hobby!

Close That Tube! Open tubes enable you to take a telescope apart for storage and transportation. This is good for the most part. And they let you handle a much larger telescope than you could otherwise.

But does the open tube affect the performance of the scope? You bet it does! For the most part, performance suffers. Unless you live in a desert area with no moisture, no wind at night, and no stray light — don't we all wish — open tubes degrade the optical image. Why? Dew on the optics is one reason. Dirt is another. And, although open tubes promote cooling and eliminate tube currents, they also let the observer's body heat to drift into the optical path. Guess what this does?

At the '88 Texas Star Party, we were observing faint planetaries with Jack Marling, and had a group of observers standing around the scope. It was a cool night, and the seeing wasn't too bad. Suddenly, with his eye to the eyepiece, Jack asked,"Okay, who just walked in front of the scope". It was me! Jack said the image in the scope just started wavering and almost disappeared. I looked through the scope just to see what affect it really had to have someone stand in front, and under the open front end of your telescope. It's amazing just how much distortion a little body heat has on the image in the eyepiece. Try it yourself.

Body heat will have the same effect as it drifts through the optical path, no matter if it's in front of the scope or through the middle of the optical path. The image in the eyepiece will look like it's doing the hula, which may be entertaining, but not when you are trying to draw a small planet.

Open tubes also let in stray light, and stray light affects the contrast and resolution. Just like the refractor boys use light baffles to cut down on reflections, we Newtonian builders should show our appreciation for a nice rough flat-black tube interior. Try mixing a little sawdust in the paint when you paint the inside of your tube. This also means that you should also paint everything visible inside the tube flat black. If you can't use a solid tube to block out all stray light, at least wrap black cloth around your tube.

Lighten Up If you plan on building a new Dobsonian mounting in the future, here are a few ideas to consider.

Contrary to the older ideas, we find that the lighter the design is, the more pleasant it will be to use. That 500-pound telescope is a real pain to move around and set up; it is also harder to hand track than one that moves easily.

But watch out for a mount that moves too easily. Many telescope makers think they can mount a telescope on wheels or ball bearings to make it move easier. It works. Unfortunately, we have not yet seen one that works as well as the old Teflon on Formica yet. A mounting that moves too easily can be more trouble than one that is too stiff.

A light large scope is much easier to move around and hand track the stars than you might think. It uses good old Teflon and a rough-textured Formica. See David Kriege's article in *TM#35*, about using rough formica vs smooth. I have since tried #7181 Formica, and found it to be excellent. In *TM#38*, Kriege mentioned another type of counter top that's even better.

The object is to build the scope light enough to be easy to transport and use, while keeping the mounting stable enough. A telescope that just vibrates and shakes all the time is practically worthless, and completely unusable in any breeze at all.

This is where reading *Telescope Making* and attending star parties proves invaluable. Save yourself a lot of headaches by finding out what others have done. Concentrate on discovering what works best and use those ideas when building your scope. Don't be afraid to try a new idea you have come up with. Then attend some star parties and show other people what you've done. As telescope makers, we count on each other for the new ideas that keep improving our telescopes year by year. That's what our hobby is all about.

When I took our 18-inch f/6 to the 1988 Texas Star Party, John Dobson came by and looked it over very closely. He took a few photos of it and said, "I'm going to show my friends how the Dobsonian should have been designed in the first place." Thank you for the compliment, John.

Of course there was room for improvement in the Dob built, but remember, there is almost as much room left for improvement left in today's models. Perhaps you will be the one to take the evolution of the Dobsonian on to its next step.

Tom Clark
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Sarasota, FL 34243

The Solar Newtonian

Requirements for observing the Sun are contrary to the demands of nighttime observing. While deep-sky observers long for a bigger light bucket to capture every photon of the faint fuzzies so dear to their hearts, the solar observer requires a light sieve that leaks 99.999 percent of the light that pours through it.

For the solar observer, bigger is not better. Daytime seeing is often so poor that the maximum useful aperture for a solar telescope is 4 inches about 90 percent of the time. A small solar Newtonian, in which bare glass reflecting surfaces are used, meets the solar observer's requirements nicely. It gives an image of comfortable brightness and in resolution is limited only by seeing. However, few amateur astronomers seem to have ever heard of a solar Newtonian. You won't find them in any telescope catalog so the only way to get one is to build it.

The perfect starting point is that 6-inch f/8 to f/10 reflector that has been gathering dust in your basement or garage for years. A 4.25-incher or even a 3.5-inch department-store special also make good starting material. Any of these instruments will supply almost everything you need for the job. The primary mirror need not be one of those fabled 1/20-wave gems; poor daytime seeing allow 1/4-wave mirrors to shine. Larger scopes can be used but must be stopped down most of the time.

Needed: a Density of 5

The primary task of the solar Newtonian is image brightness reduction. Optical filters are usually described in terms of optical density, a quantitative term given by the equation:

$$D = -\log(I_o/I_i)$$

where D is the optical density and I_i and I_o are the intensities of the light entering the filter and leaving the filter, respectively.

For safe and comfortable solar viewing, the brightness of the Sun must be reduced by a factor of 100,000. This requires a filter for which D = 5.

Reflecting surfaces can be treated as filters by assigning an optical density for reflection calculated by replacing Io in the above equation with the value for the light reflected. Optically polished Pyrex glass reflects from about 5 percent to about 7 percent of the incident light, depending on the angle of incidence. Glass reflects a higher percentage at higher angles of incidence.

Plugging the decimal fraction equivalents of these percentages into the equation for optical density gives values of D from 1.15 to 1.3. In a Newtonian reflector, 1.3 approximates the reflection from the primary mirror and 1.15 approximates the reflection from the diagonal, which is inclined. The nice thing about optical densities is that you add them to get the total optical density of the system.

It has often been said that a Newtonian reflector can be converted for solar observing merely by removing the aluminum coating from the two mirrors. However, that gives a total optical density of about 2.5, dangerously short of the need value of 5. In a two-mirror telescope the solar image is about 350 times too bright. While you might not suffer permanent eye damage after looking through the eyepiece, you would be able to study a colorful after image of the Sun for quite some time.

Reflections Polarize

If there were no factors except simple reflection, two additional unaluminized diagonals would be needed to give an adequate optical density. Fortunately for the TM — but unfortunately for the sellers of diagonals — something else is going on. When light strikes a glass surface at an oblique angle, as is the case with the diagonal mirror, the reflected light is polarized just as if it had passed through a polarizing filter. At a critical angle of incidence, called the Brewster angle (roughly 53° for Pyrex glass), the reflected beam is completely polarized. Because of this polarization only three reflections are needed to obtain an overall value for D of about 5. The diagram shows one configuration for a three mirror solar Newtonian. Consideration of each reflection in this optical train illustrates how polarization affects the amount of light transmitted.

The light from the Sun striking the primary is unpolarized. The angle of incidence is close to 0° so the primary reflects about 5 percent of the light and the reflected light is essentially unpolarized. This light beam strikes the diagonal at a 45° angle, very close to the Brewster angle, so the light reflected from the first diagonal is mostly, but not entirely, polarized. The plane of the polarization is perpendicular to the plane of the paper. About 7 percent of the light striking the diagonal is reflected, just as would be the case neglecting polarization.

Because the plane of polarization of the second diagonal in the diagram is parallel to that of the first diagonal, when the beam strikes this diagonal the polarized portion of the light is reflected with greater efficiency than would be calculated neglecting polarization. The light arriving at the focus of the telescope is highly polarized and much brighter than would be expected for three reflections from unsilvered glass. This configuration is analogous to passing a beam of unpolarized light through two polarizing fil-

The solar Newtonian makes visual solar observing and photography a matter of routine. The 'scope shown is used for both kinds of observation.

ters with parallel planes of polarization.

However, if the second diagonal is rotated about its axis, the planes of polarization are no longer parallel. As with polarizing filters, the intensity of the light decreases, reaching a minimum when the rotation reaches 90°. The plane of polarization of the second diagonal is now parallel to the plane of the paper and the two diagonals form a crossed pair of the polarizers. In this configuration, the light is almost completely unpolarized (or if you want to get technical, is circularly polarized) and the intensity is significantly less than would be calculated for three reflections. If the rotation is continued another maximum is reached at 180° and another minimum at 270°.

These changes in polarization and intensity with rotation of the second diagonal lead to three types of solar Newtonian, one in which the second diagonal can be rotated to vary the intensity and two in which the second diagonal is fixed, either in the maximum brightness/maximum polarization configuration. There are advantages and disadvantages for each type. These will be discussed more fully below.

Removing Aluminum

Before we get into the details of construction there are a couple of practical problems to take care of. The most difficult of these is getting rid of the aluminum coatings on the old mirrors. A professional aluminizer will do this for you at about the same cost as aluminizing. However, with a few precautions, you can do it yourself. WARNING! THIS PROCESS USES CONCENTRATED HYDROCHLORIC ACID WHICH IS CORROSIVE TO HUMAN SKIN AND JUST ABOUT EVERYTHING ELSE EXCEPT GLASS AND PLASTIC. FUMES FROM THIS ACID ARE EXTREMELY IRRITATING TO THE EYES, NOSE, AND THROAT. INHALING THESE FUMES MUST BE AVOIDED. WEAR RUBBER GLOVES AND PROTECTIVE GOGGLES AND HANDLE THE CONCENTRATED ACID ONLY OUTSIDE OR IN AN AREA WITH GOOD FORCED VENTILATION.

If I have already scared you off, send the mirrors to your favorite aluminizer, or try to interest a local chemistry teacher in doing the job in return for some viewing time when you finish your scope. If you're still with me, proceed as follows.

Obtain a pint of concentrated hydrochloric acid, also called muriatic acid, sold by swimming pool supply houses and many hardware stores. Put about a pint of cold tap water in a plastic or glass tray big enough to hold the mirrors you want to treat. In the open air, slowly pour a pint of concentrated hydrochloric acid into the water and stir the mixture with a wood, glass, or plastic stirrer. The dilute acid does not fume and the work can be moved inside to a place where there is no chance of another person or a pet coming in contact with the acid. The dilute acid will stain most finished surfaces so be careful where you spill it.

Wearing your non-leaking rubber gloves, carefully slide the mirrors aluminized side up into the diluted acid. Stir the acid occasionally and swab the surfaces with a cotton ball. Examine the surfaces with a bright light for any shiny specks of aluminum that may remain and after all are gone let the mirrors stand for an extra hour or two.

Stripping an aluminum coating can take anywhere from a few minutes for a bright aluminum coating with no overcoating to two or three days for a coating overcoated with silicon oxide. It will come off eventually; if it does not, you have a silver-coated high-quality mirror that you shouldn't have used in the first place.

When the coating is gone, take the mirrors out of the acid (with rubber gloves, of course) and put them in a glass or plastic container, again face up. Flush the spent acid down the toilet and follow it with several flushes. Rinse the mirrors several times with cool water, then give them a final rinse with distilled water and prop them up on edge in a dust-free place to dry. You have now completed the trickiest part of

the conversion.

Back-Blackening the Flats

Light passing through your now-bare mirrors will be reflected back along the optical axis not only from the front surface but also from the back surface of the mirrors. This is a problem because you may see double images. Fortunately, there is an easy solution:paint the backs black. If the backs of the diagonals are not already ground to a matte surface, grind them for a couple of minutes on a flat glass or metal surface with #120 Carborundum or work them awhile on 100-grit sandpaper. It is desirable to check the diagonals for flatness because grinding may release strains in poorly annealed glass.

It's not worth the trouble to grind the back of the primary. Protect the front surfaces if the primary and the diagonals with masking tape and spray the backs and edges with two or three coats of black paint. If necessary clean the front surfaces with alcohol or a warm solution of dishwashing detergent, then rinse and dry as before.

You might expect that the primary would be heated considerably by the absorbed sunlight. However, even after a half hour of observing you will find that the mirror is only slightly warmer than the rest of the telescope because the paint is a good radiator of heat.

With these messy details out of the way, you are ready to convert your obsolete Newtonian to a Super Solar Scope. If you are starting from scratch consult one of the many books or articles that explain how to build a simple Newtonian before proceeding.

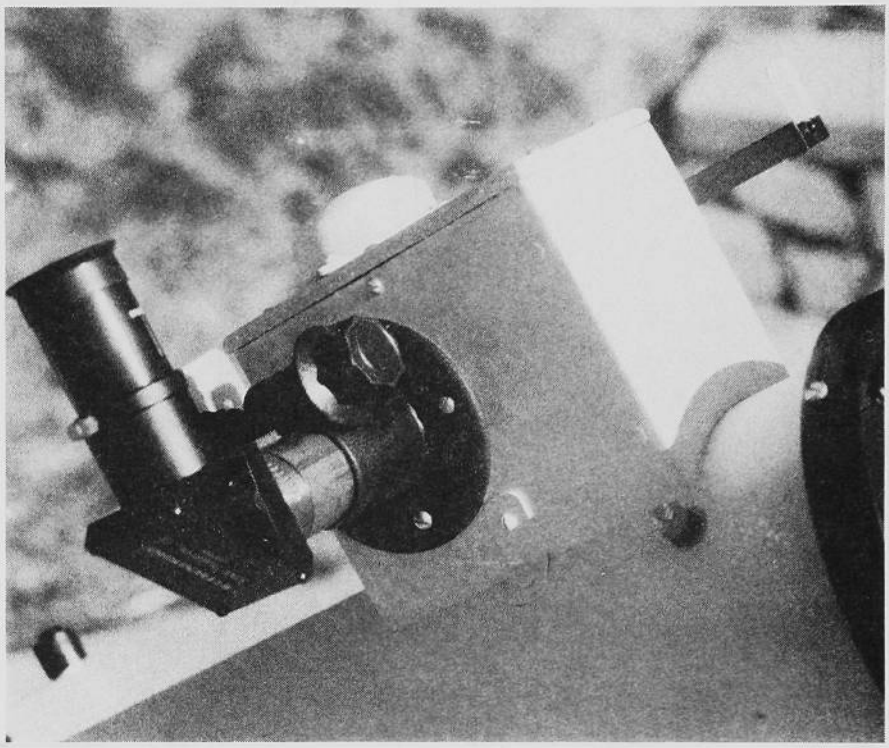
The Simple Solar Newtonian

Conversion consists of inserting a solar diagonal (the same as a star diagonal but with an unaluminized mirror) into the focuser of your de-aluminized Newtonian. However, because the solar diagonal increases the distance that the light must travel before reaching the eyepiece, it is necessary to move the primary mirror closer to the first diagonal by an amount at least equal to the light path through the solar diagonal. You must also provide the open end of the tube with some means of holding an off-axis aperture stop.

But where do you get a solar diagonal? These were once almost a standard accessory for small refractors. If you're luckier than I am you may find a one at a flea market and your conversion will be completed. Alternatively, you might find a mirror-type star diagonal that can be converted to a solar diagonal by removing the aluminum coating. (Check before doing anything that the star diagonal unit is a mirror type and not the more common prism type and that the mirror can be removed without a can opener.)

How to Make a Solar Diagonal

Better yet make your own. It's an easier job than you might think. You will need the following items: a 1-inch PVC pipe T (inside diameter about 1.25 inch), a 1.25-inch brass slip joint extension (a section of chrome plated brass tubing about 8 inches long and 1.25-inch inside diameter at one end and 1.25-inch outside diameter at the other), three 6-32x3/4-inch machine screws, some quick-setting two-part gap-filling epoxy adhesive, a 1-inch diameter wood dowel, a rubber O-ring with 1-inch inside diameter and 1/8-inch cross-sectional diameter, some carpenter's wood filler, some flat black spray paint, and a 3/4-inch or 1-inch minor diameter optical flat. All of these things except the optical flat can be purchased at your local do-it-yourself hardware. A drill press and a table saw or miter box are handy you can get by with a fine tooth hacksaw, an electric drill, and a little care.

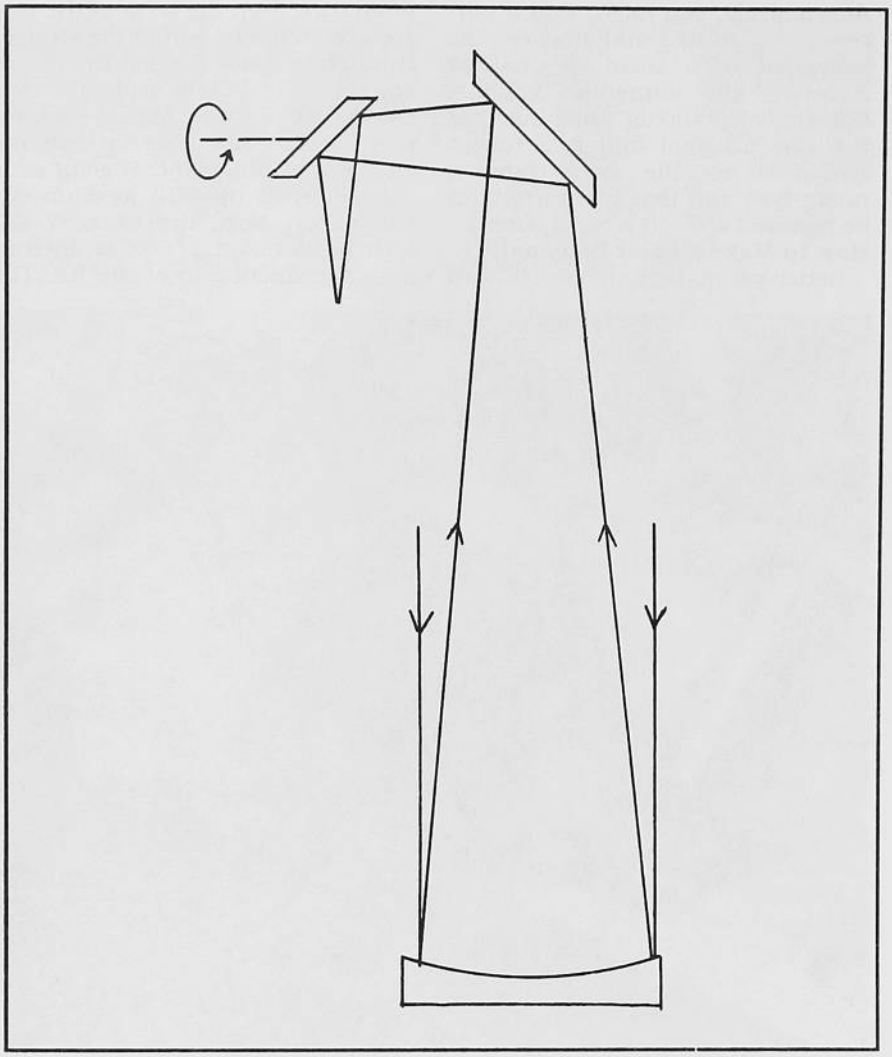


The photo, which shows all the parts except the diagonal mirror, just about tells it all. Cut about 3/8 of an inch from the stem of the pipe tee and from one end of the straight through section, making the cut as square as possible with the tee. Depending on the maker, the tee may or may not have an external shoulder at this point. The cut ends can be trued up with medium grit sandpaper. Next, drill three 7/64-inch holes about 1/8 of an inch in from the uncut end of the tee. The first hole should be at the top of the tee and the other two spaced 120° apart. Make sure that the holes are perpendicular to the body of the tee. If you have a 6-32 tap use this to thread the holes; if not, carefully screw a 6-32 machine screw into the hole to thread it.

Lay the tee aside and carefully cut one end of the dowel at a 45° angle. Check the angle against a known 45° angle and true it up by sanding if necessary. Cut the dowel off square about 2.5-inch back from the point of the angle.

From the small end of the slip-joint extension, cut a piece about 1.5-inch long, squaring up the cut end by sanding. Cut off the other end of the slip joint extension about 1/2-inch below the shoulder, then cut the larger diameter section to a length of about 1.5-inch above the shoulder, again truing up the ends.

Roughen the small end of this section of tubing and one end of the first section of tubing with coarse sandpaper. You have now com-



pleted all of the complicated machine work and are ready to assemble the housing for the solar diagonal. Spread a fairly thick layer of gap-filling epoxy adhesive on the sanded end of the smaller section of tubing and insert it into the stem of the tee. Be sure that it is centered and square with the tee and hold it in place until the adhesive sets up, usually about 5 to 10 minutes.

In the same way, cement the small end of the larger section of tubing in the cut off arm of the tee. After the epoxy has thoroughly hardened, remove any blobs and runs of adhesive from both the outside and inside of the assembly with a sharp knife, a fine file, or sandpaper. Cover the outside of the assembly with masking tape and spray the inside with two to three coats of flat black paint. At the same time, paint the end piece of dowel.

When the paint is dry, cement the optical flat to the angled end of the dowel with epoxy adhesive. The flat should be carefully centered and held in place until the adhesive sets. Now comes the final assembly. Slide the O-ring on to the dowel as close to the flat as possible and insert the dowel in the uncut arm of the tee. Screw the machine screws into the three holes but do not tighten them against the dowel. Looking through the stem of the tee rotate the dowel and move it in and out until the flat is centered in the opening. Now tighten the screws against the dowel and adjust them until the flat appears perfectly circular.

These adjustments may be made more accurately if lengths of tubing are inserted in the two arms of the assembly and you use them to set the angles. When you are satisfied that the adjustment is as good as you can get it, fill the gap between the dowel and the inside walls of the tee with carpenter's wood filler or other opaque filler, taking care not to force the filler more than 1/2 an inch or so into the arm of the tee. The filler will prevent any movement of the flat and more importantly will keep stray light out of your now completed solar diagonal.

For a neater job carefully cut off the dowel flush with the end of the tee and paint the cut end.

You now have a fine, relatively inexpensive solar diagonal. Reassemble the telescope. Remember that this solar diagonal adds roughly 2.5 inches to the optical path length. When you drill new holes for mounting the primary mirror, it is better to move it a little more than you calculate than a little less.

Collimating a Solar Telescope

Collimation is a little more difficult than collimating an ordinary Newtonian is, but it is done basically the same way. Without inserting the solar diagonal in the focuser, point the telescope at a brightly lighted wall or bright patch of sky but not at the Sun. You will see the usual Newtonian pattern of the diagonal, the primary mirror, and the focusing tube, but you will probably not be able to see the pupil of your eye. Adjust the primary and diagonal in the usual manner until you have a circular diagonal centered in the focuser extension tube and in the reflection of the primary mirror.

Now insert the solar diagonal in the focuser and, using an eyepiece that gives about 50x, aim at the Sun. After getting a sharp focus rotate the solar diagonal to give the image brightness that you want. If the limb of the Sun is not uniformly sharp or if the image is brighter on one side than the other touch up the adjustments until the image is satisfactory. Your Super Solar Scope is finished. In using this telescope, remember that an odd number of reflections gives a north up, east-west reversed image.

This telescope has the usual Newtonian problem of finding a position for the primary that will allow focusing both with low power eyepieces and at the focal plane of a camera, so it is not suitable for photography. Furthermore, hanging a camera on the stacked focuser and solar diagonal is a mechanically flimsy arrangement, especially since few Newtonian focusers have any means for locking things in place. It is also difficult to get reproducible exposures because the brightness of the image is very sensitive to changes in the rotation of the solar diagonal.

The Photo-Visual Solar Newtonian

The photographs show the main

features of my 6-inch f/8 solar Newtonian. The primary mirror saw first light in 1947 as a 6-inch f/9 Newtonian. Unlike myself, it has grown thinner with the years as it was reground and refigured to f/ratios from 4 to 12, finally coming to rest at f/8. The tube is relatively new — it's thirty years old — and consists of equal parts of aluminum and Bondo body filler.

Optically this telescope is identical to the simple conversion described above, the differences are only mechanical. I designed it to be equally capable of prime-focus photography and visual use. The photos show it in the minimum brightness/minimum polarization configuration. Much of the construction is obvious from the photographs, so I will only cover the important general features and considerations.

To facilitate prime-focus photography, I brought the focal plane out 2 inches beyond the end of the focuser. For visual use, I use a standard star diagonal in the focuser that also returns the image orientation to that of an ordinary Newtonian. The hose clamp around the draw tube holds everything in place. The width of this clamp must be allowed for in calculating the optical path length.

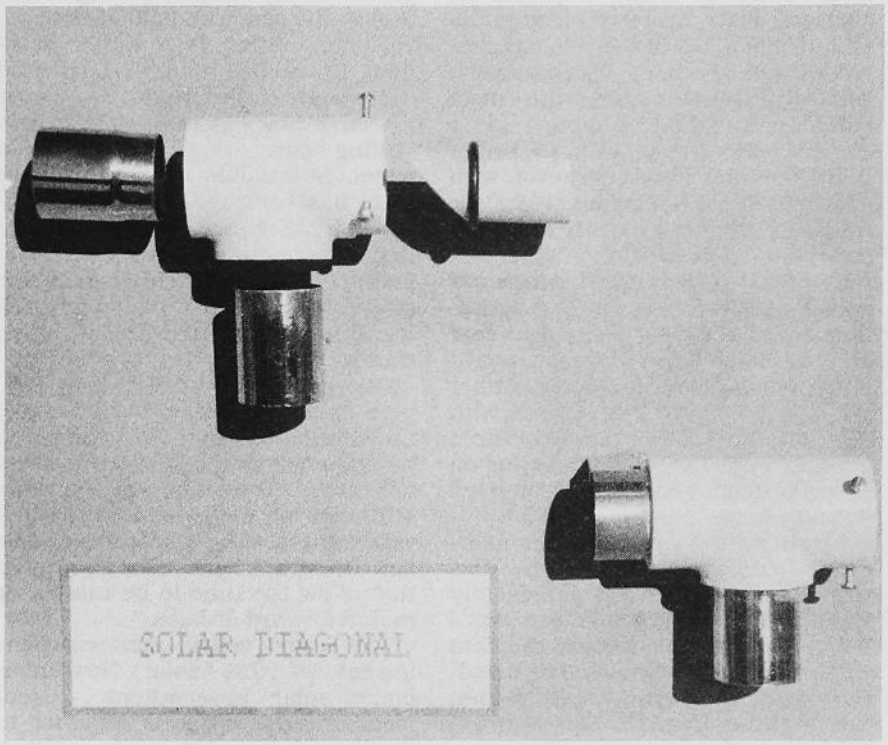
Because of the long path outside the main tube, it is necessary to know the exact focal length of the primary and to make an accurately scaled drawing of the proposed telescope to work out the dimensions of the various parts, particularly the diameter of the first diagonal and its distance from the primary mirror. This diagonal should be only large enough to give full coverage for the image of the Sun, so it is important to calculate or measure the diameter of the solar image given by your mirror. My primary mirror has a focal length of 48.5 inches and gives a solar image about 0.42 inches in diameter. The optical path between the first diagonal and the focal plane is 11.5 inches long, so the distance between the primary mirror and the center of the first diagonal is only 37 inches. To avoid serious vignetting of the solar image, I had to replace the original 1.25-inch minor axis diagonal with one of 1.75 inches minor axis.

The second diagonal is mounted in the 4-inch-wide by 6-inch-long by 4.5-inch-high turret on top of the tube. This turret is made from 1/2-inch thick walnut painted flat black inside. Plywood would do as well. The bottom is shaped to fit the 7-inch tube to which it is attached by screws inserted from inside the tube and by external angle brackets. In the top is a 2-inch circular hole centered over the 1.25-diameter exit hole in the main tube.

Mounted over the exit hole in the main tube is a 1-inch thick and 2-inch by 2-inch wooden block, the bottom of which is shaped to fit the tube. The 1.25-inch diameter hole in this block is accurately centered and squared with the main tube. This serves as an alignment aid in the finished telescope. The second diagonal (the dealuminized 1.25-inch minor axis diagonal from the original Newtonian) is mounted by means of three adjusting screws on a 2.5-inch square plate of 1/8-inch thick aluminum. A normal spider mounting could be used but the plate saves a couple of inches of turret height. It is necessary that this diagonal be mounted as close to the main tube as possible and that the focuser likewise be mounted as close as possible to the diagonal to keep the external optical path length short.

In the completed scope, the diagonal and its cell are inserted through the hole in the top of the turret and, after rough alignment, the plate is screwed to the top of the box with four wood screws. To keep out dust and light, I have fastened a plastic pipe cap over the mounting plate with screws. There are two 1.5-inch diameter holes in the turret, one on the back and one the side.

I mounted the focuser over one of these with wood screws and covered the other a plywood disk. The focuser base was originally shaped to fit a round tube, but a little work with a hacksaw and file flattened its base to fit my flat turret. This arrangement allows the optical configuration to be switched by removing a few screws, repositioning the focuser and the diagonal plate, and touching up the collimation, a process that takes five minutes or so.



I collimate my photo-visual solar Newtonian in two steps. With the second diagonal and its mounting plate removed, I insert a foot-long section of 1.25-inch diameter brass tubing fitted with cross hairs at both ends through the hole in the top of the turret and into the wooden block mounted over the main tube exit hole.

This tube is carefully squared up with the main tube. I align the primary and first diagonal in the usual way for Newtonians by sighting through this tube with the telescope pointed at brightly lighted clouds. After removing the sighting tube I mount the second diagonal and center it in both the main tube exit hole and the focuser by careful measurement. The second diagonal is then adjusted until all the reflec-

tions are concentric and circular. I have done the final tweaking with the scope pointed at the Sun as described above.

Performance

In the maximum brightness/maximum polarization configuration, the solar image in the photovisual Newtonian was much too bright for visual observation, but I could reduce it to a comfortable level either by using a polarizing eyepiece filter or by replacing the star diagonal with the solar diagonal described above. Mechanically, this arrangement gave the most stable and balanced mount for a camera. The image was so bright that exposures were short even with ASA 25 films, and too bright for ASA 200 films even with an exposure of 1/1000 second.

In the minimum brightness/minimum polarization configuration, the telescope gives images that are comfortably bright for photography and visual observation at either f/8 or f/20. Typical exposures with ASA 200 films are in the range from 1/60 to 1/250 second depending on whether the aperture was stopped down or not.

Mounting the camera in the minimum brightness position has turned out to be quite satisfactory and has the added advantage that I don't have to look toward the Sun when I focus the camera. The disadvantage of this arrangement is that the brightness cannot be controlled to any significant degree with a single polarizing filter.

Over the past year this telescope was used by number of observers. A few of them thought the image too bright, particularly for prolonged viewing at full aperture. By measurement, the optical density of the telescope is about 4.3 — well within the safe range. Nonetheless, I now recommend a neutral density filter of roughly 15% transmission to reduce the image brightness, and recommend such a filter to anyone building a similar solar telescope.

In my location, summer seeing often justifies using full aperture, but in the winter the stop almost always gives the sharper image. The opening in the stop shown is about 2.4 inches diameter. The mounting ring began service many years ago as part of the cell for an aperture filter. It is constructed from a number of rings cut from particle board and glued together. Three sheet metal screws hold it firmly on the end of the tube. The stop is held in place by turn buttons for easy removal.

The bar fastened to the back side of the turret is a solar sight consisting of a small aluminum plate drilled with a 1/8-inch hole at the front end of a foot long oak strip and a piece of white laminate at the other. A spot of black paint marks the position of the Sun's image when the Sun is centered in the telescope. The sight is particularly useful in photography because it provides very easy centering of the Sun in the camera's field of view.

The mounting is a rather standard Dobsonian mount. I reduced the weight of the mount by boring ten large holes in each upright and cutting away most of the front panel. Not visible is that the base plate has been reduced to a three-spoked wheel. A sliding balance weight is mounted on the tube to permit ready balancing when the camera is used. Also handy for photography is the split ring altitude clamp.

Felt pads bear on a 2-inch PVC pipe flange mounted outboard of the altitude bearing. This clamp can be tightened so that the telescope is not disturbed by film winding while still allowing easy movement when you want it. The telescope saddle has two transverse clamps on top that allow the tube to be rotated or moved forward or back.

The easy setup and excellent images of this solar Newtonian make solar observations a real pleasure. The image is superior to that given by any aperture filter, particularly when the seeing is good. The total cost, including buying the new first diagonal, came to much less than that of a moderately priced 3-inch aperture filter.

I thank the staff of the Bays Mountain Planetarium for the photographs used in this article.

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Over-the-Aperture Solar Filter

Two basic types of solar aperture filters are available on today's market: aluminized Mylar polyester film and glass metallized with an alloy or mixture usually containing nickel, chromium and iron. Filters cost from $10 to $100 depending on size, type and mounting, and are available to the amateur astronomer from R. Tuthill (Solar Skreen aluminized Mylar polyester film) or Thousand Oaks Optical Co. (metallized glass filter and aluminized polyester film filter). I have used all of these filters over the years; what I report in this paper is the result of this experience.

Solar Skreen filters consist of two layers of 0.5 mil film aluminized on one side only and mounted as a sandwich with the aluminum as the filling. The film must be slightly wrinkled — stretching an aluminum plastic film will destroy the integrity of the coating — but shows no texture when examined using a 10X magnifier. Mounted as directed I saw no pinholes in two examples.

The Thousand Oaks Polyester filter is a fairly stiff flat sheet about 1.5 mils thick aluminized on both sides. Both surfaces show a pattern of fine closely spaced parallel lines which appear to be in the plastic substrate. This filter had two or three randomly scattered pinholes per square inch. For naked eye solar viewing the bright diffraction patterns resulting from the many pinholes made this filter almost useless.

Thousand Oaks Glass filters showed no texture in the metal film and contained only a very few pinholes in the two examples I examined.

Solar Skreen, Thousand Oaks Polyester, and Thousand Oaks Glass filters, stopped down to 3 inches, were mounted on a Celestron C-8 fitted with a 15mm Plössl eyepiece, giving 130x at f/27. My standard of comparison was my stopped-down 6-inch solar Newtonian at 100x and f/20. The Solar Skreen and Thousand Oaks Glass filters gave sharply defined images seen against an almost black field with faintly visible halos around the solar disk. I judged the blue-gray Solar Skreen image to be about twice as bright as the orange Thousand Oaks Glass image. Viewing with the Thousand Oaks Glass filter was improved by covering the observer's head with a black cloth.

Under poor-to-fair seeing there was no significant differences in contrast or resolution between the Solar Skreen and Thousand Oaks Glass filters. The solar Newtonian provided slightly better images in both contrast and resolution. Under good seeing conditions, the Solar Skreen filter had a small but significant advantage both in sharpness and contrast, particularly when I used a Wratten #16 yellow eyepiece filter with it. This gives a rather sickly greenish yellow image but reduces significantly the blue light scattered by the aluminum film). However, the solar Newtonian gave better resolution contrast than

either over-the-aperture filter, particularly for penumbral detail, faculae, and granulation.

The Thousand Oaks Polyester filter was another matter. With this filter the entire field was illuminated with scattered light even when the sun was two or three degrees out of the field. There was also moderately bright linear texture seen in the film. Despite these serious optical flaws, it was possible to see a reasonable amount of detail in the larger spots and faculae. Small spots and low contrast features were seen poorly or not at all.

Photography with the Solar Skreen and Thousand Oaks Glass filters gave results similar to those obtained for visual use, but the Thousand Oaks Glass filter required about twice the exposure for the Solar Skreen filter. Because of the large amount of scattered light, the Thousand Oaks Polyester filter was not suitable for photography.

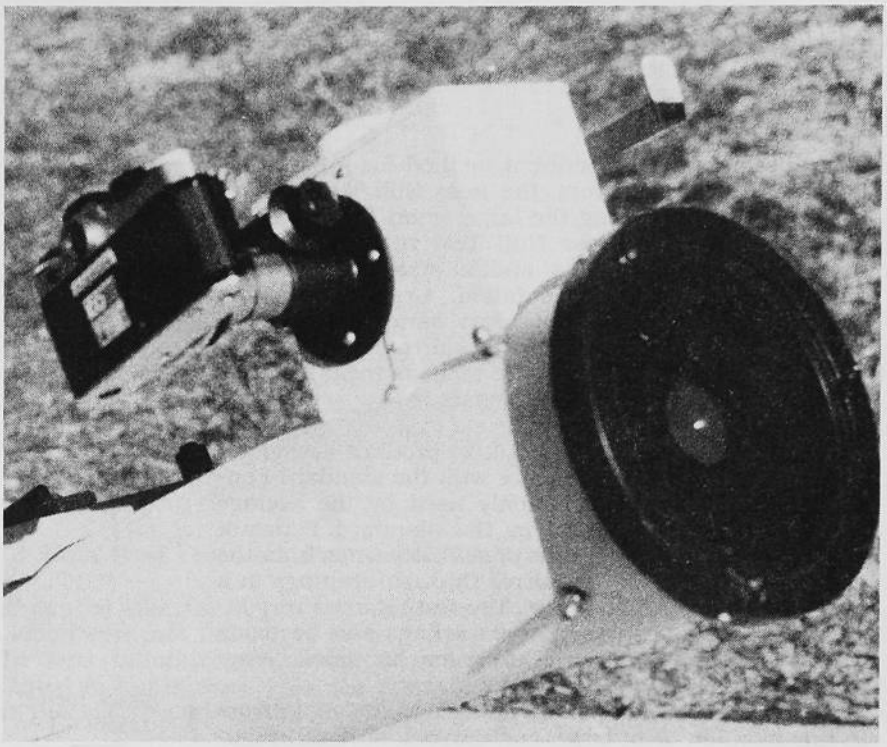
Durability is more of a problem with solar aperture filters than with most telescope accessories. Mylar polyester films, particularly the Solar Skreen, appear quite fragile compared to glass filters. However, the film is remarkably tough. These filters withstand any abuse except poking with a sharp object as well as or better than the glass filters. Pinholes or small punctures can be patched with paint or opaque tape with little harm to performance. Glass filters can be cleaned with care, following the manufacturer's directions, but aluminized Mylar film filters should only be cleaned by blowing off dust.

I haven't found either accidental damage or cleaning to be a problem with any of these filters. However, slow deterioration is a problem with both types of filters although their modes of failure are different.

Metallized glass filters slowly develop pinholes over time even if they are used infrequently and stored, when not in use, in a closed container at normal room temperature and humidity. These pinholes have no significant effect on performance and can be touched out with black paint. After a few years (6 to 10 year for three different filters), however, a catastrophic metal dandruff sets in and pieces a millimeter or more in diameter flake off. At this point the filter is no longer safe to use.

The life of the Thousand Oaks Glass filter appears to be unrelated to how much it is used. A filter which was used no more than a dozen times in 8 years failed as quickly as one used weekly over the same general period.

Solar Skreen filters deteriorate mainly as a result of degradation of the polyester film by solar ultraviolet light. Therefore, the useful life of the filter depends on the length of time it is exposed to the sun. Scraps of Solar Skreen film stored in the dark for over 10 years show



no visible change; unfortunately, solar aperture filters are not very useful stored in the dark. After almost 10 years of once or twice weekly use with 10 to 30 minutes exposure to the sun each time, for a total of several hundred hours of exposure, a Solar Skreen filter had developed only a few pinholes and some small areas of reduced density. The polyester film was still tough and flexible. These changes did not affect either the image quality or the light transmission to an observable degree.

Following this use the filter, I began to use the filter every clear day, often for an hour or more at a time. After about four summer months — 120 hours or more use — it was obvious that the filter was suffering rapidly accelerating damage. The number of pinholes had increased considerably, the thin areas had become larger and thinner and the outer layer of film had become quite brittle. The inner layer of film, being somewhat protected from light by the two layers of aluminum coating, was still tough and flexible, but was also loosing its aluminum coating. Parts of the filter covered by the mounting plate remained in like-new condition. Although it is not possible to predict what the life of a heavily used Solar Skreen filter would be, I would not expect that such a filter used every day for long periods would survive for more than 3 to 5 years.

I have not had the Thousand Oaks Polyester filter long enough to make any determination of its mode of deterioration or its expected life. However, after only three months of occasional use, it has developed a number of new pinholes, indicating that its useful life may be short.

Solar filters are a convenient way to observe the sun, requiring no alteration of the nighttime part of the telescope. They sidestep the mechanical problems that projection involves. At my site, poor daytime seeing wipes out any differences between the Solar Skreen and Thousand Oaks Glass filters roughly 90 percent of the time.

Even the inferior Thousand Oaks Polyester filter costing only $10 for a 5-inch square will allow the casual observer to see a lot of solar detail. However, at times when the seeing is good, no over-the-aperture solar filter performs as well as the solar Newtonian.

— Gerald R. Lappin

Making Precision Paraboloids is Easier with the

Ross Null Test

In this article we describe a method for null-testing large paraboloidal mirrors, the Ross Null Test, that is ideally suited for testing the large, short-focus mirrors popular today. The Ross Null Test requires a high-quality plano-convex lens and a standard Foucault apparatus for its implementation. Graphs presented with this article provide necessary parameters for setting up the Ross Null Test test for mirrors ranging from f/3.5 to f/10, for different conic sections including paraboloids, and for different test lenses.

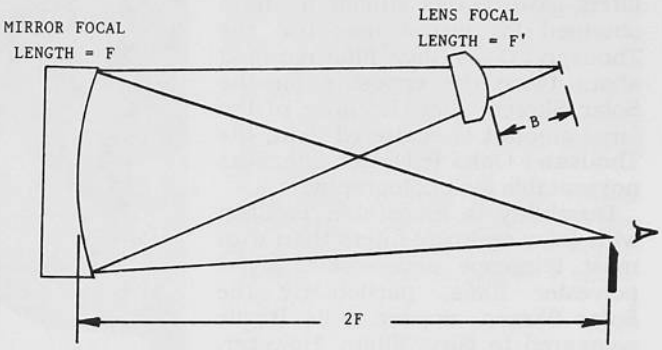
Standard Tests It is difficult to produce a smooth, fully corrected aspheric surface with the standard Foucault test techniques commonly used by the average amateur telescope maker. In the standard Foucault test, you measure the radius of selected zones from the center to the edge of the mirror through openings in a mask mounted on the mirror. The test requires very little special equipment and the readings can be made with a sufficient degree of precision for small, long-focus mirrors.

There are significant disadvantages to testing mirrors in this manner. With large, fast mirrors, surface irregularities that will have a deleterious effect on image contrast may be overwhelmed by strong parabolic shadows, and may pass unnoticed. More importantly, the zonal measurements for these mirrors should be made to a degree of precision sometimes greater than the test will allow.

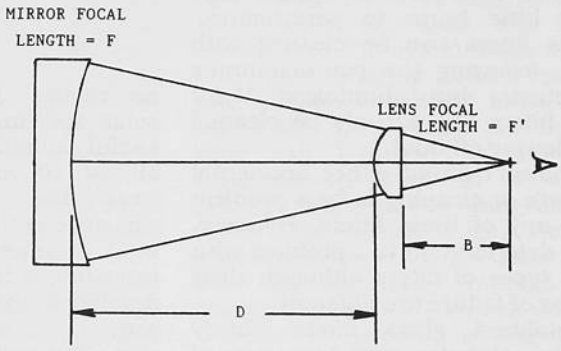
The ideal test for any telescope optical system is a null test. In a null test all the rays arrive at a common focus. When a knife edge is placed at the exact focus of these rays the whole mirror darkens uniformly. Rays emanating from defective zones do not reach the same focus causing tell-tale shadows to appear projected on the mirror surface.

Null Tests When you test a spherical mirror at the center of curvature with the Foucault test, you are using a null test. In a parabolic mirror, however, each zone has a slightly different radius. The mirror therefore suffers from spherical aberration at the center of curvature and does not produce a null. As the aperture increases and/or the mirror's focal ratio decreases, the quality of the null becomes worse.

Autocollimation is the best bench test for a parabolic mirror. It employs an optically flat mirror, preferably as large as the paraboloid. The telescope mirror collimates the light from a tester slit placed at its focus. The large optical flat reflects the collimated beam of light back to the telescope mirror which re-focuses the light at the tester's knife-edge.



Dall Null Test Layout



Ross Null Test Layout

Figure 1: Null Tests Compared

The autocollimation test is quite sensitive to the parabolic mirror's figure because the light bounces off the mirror twice. Accordingly, irregularities are doubled in depth. The autocollimating mirror does not have to be exactly flat, but must be extremely smooth. Such mirrors are very expensive. Consequently, few amateur telescope makers will have the resources to use this test.

Refracting Null Tests The spherical aberration at

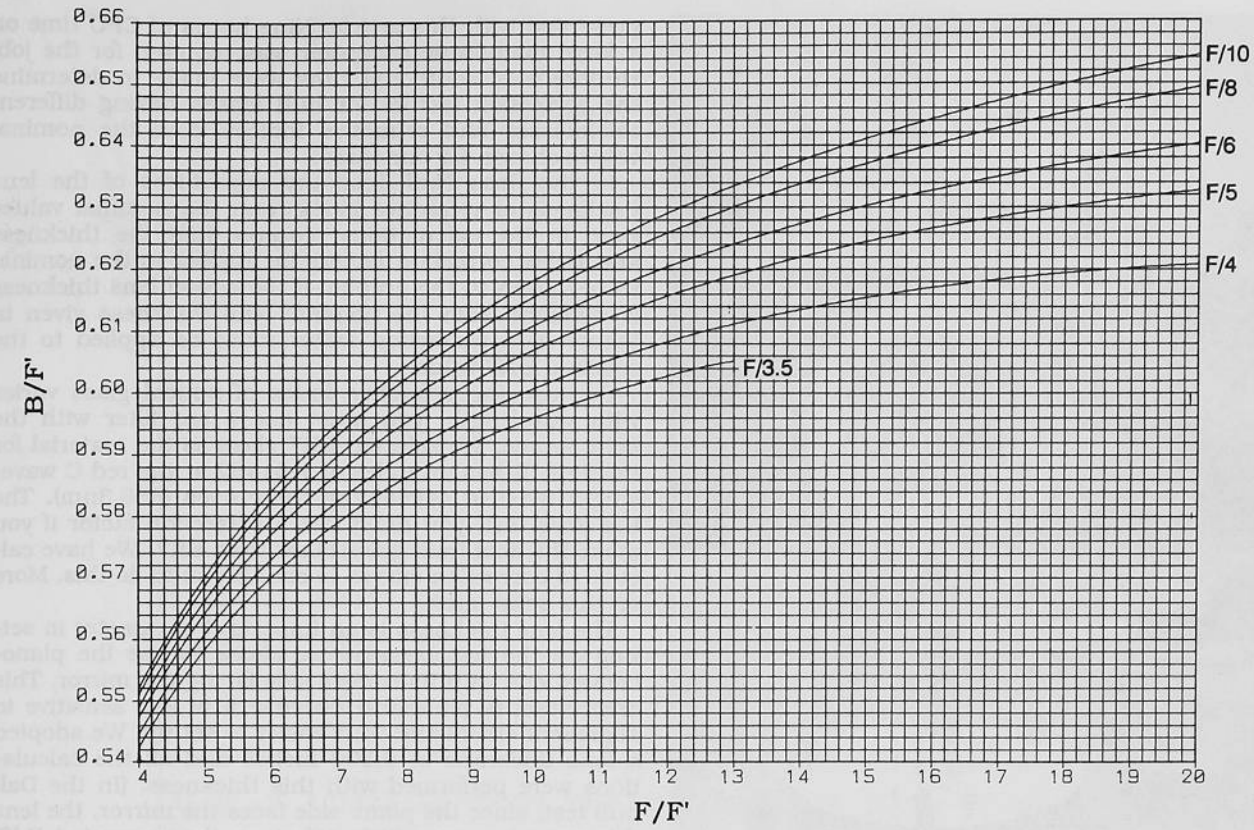


Figure 2: Ross Null Test Parameters for Paraboloids

the center of curvature a paraboloid can be effectively cancelled, or "nulled," by placing a small lens into the beam of light from the tester. The lens introduces spherical aberration in an amount equal to but of the opposite sign of that expected from the mirror under test.

There are two null lens tests suitable for the amateur telescope maker: the well known Dall Null Test and the little known Ross Null Test. Both tests are capable of testing conic sections other than the parabola, used in various Cassegrain reflector configurations, i.e. the hyperbolic primary for a Ritchey-Chretien, and the elliptical primary for the Dall-Kirkham. This offers a the telescope maker a significant advantage over the auto-collimation test.

In both the Ross and Dall null tests, departures from a true conic section (paraboloid, ellipsoid, hyperboloid) are readily seen and interpreted as a non-uniform null.

Ross Null *versus* Dall Null The major difficulty most telescope makers have with the Dall and Ross null tests is calculating the spacing between the mirror and lens needed to produce an accurate null. A graphical method of setting up the Dall null test was published in *S&T*, September 1976, p. 210, by Stoltzmann and Hatch. That article extended the scope of the Dall Null test to allow mirrors other than paraboloids to be tested with the single lens arrangement invented by Horace E. Dall. In this article we have explored the Ross Null Test in a fashion similar to the Dall null test.

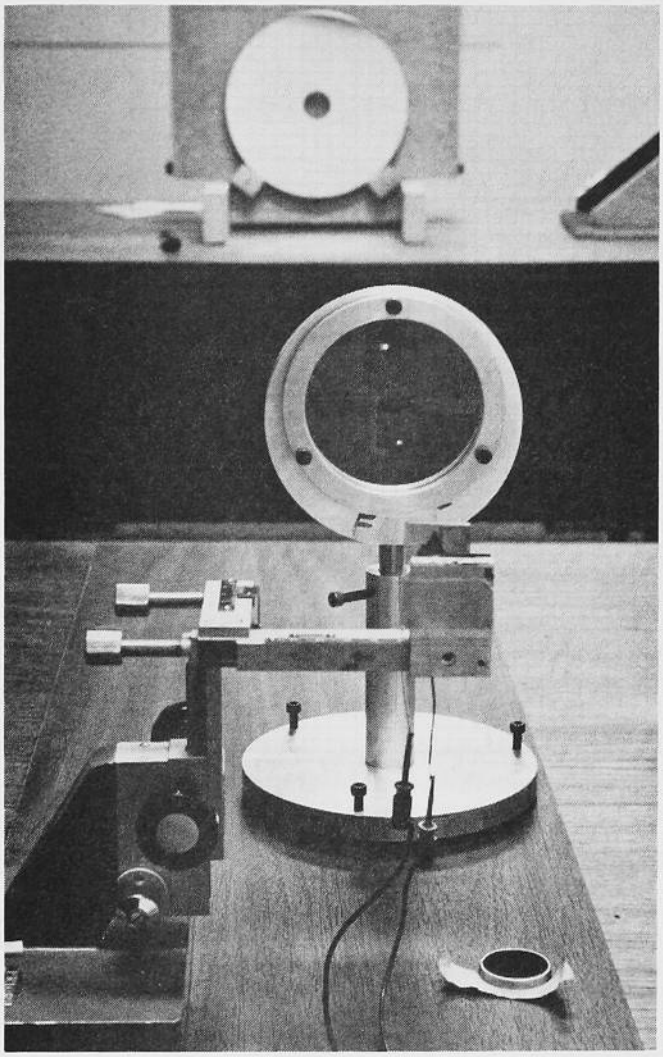
Figure 1 shows schematically the main differences between these two tests. There are two major differences between the tests. First, in the Ross Null Test the null lens is used in a "double pass" arrangement; in the Dall test light passes through the Dall null lens once. This requires the Dall null lens to be used slightly off axis, as well as being as small as possible.

In the Ross test, the convex surface of the plano-convex lens faces the mirror; in the Dall test the plano surface of the lens faces the mirror.

The Ross Null Test has many advantages over the Dall Null Test. It is easier to set up and align, and it is capable of a more accurate null. Furthermore, the Ross setup is much simpler and more easily adapted to a standard Foucault tester. In the Dall null test, the lens holder/light source requires precision machining, and the null lens must be as small as possible to keep the separation of source and knife edge small. As a consequence, nearly 100% of the Dall null lens diameter is used. The Dall lens must therefore be excellent quality from center to edge. Lenses that are small and well figured to the edge are difficult for the amateur to make and expensive for the amateur to purchase. However, a relatively large lens can be used to advantage in the Ross test because of its on-axis testing arrangement. Such lenses are relatively easy to make and inexpensive to buy.

Graphs for the Ross Null Test To implement the Ross Null Test, the Foucault tester, the null lens in a suitable holder, and the mirror must be spaced correctly. The accompanying graphs allow you to calculate the correct spacing between the optical elements. We have chosen to use the same graphical approach to the Ross Null Test parameters as those used previously to describe the Dall null test.

The graphs presented here can be used in the same fashion as Dall's original graph presented in *Amateur*



Figuring a paraboloid can be as simple as figuring a sphere with the Ross Null Test. Using a simple Ronchi screen or knife-edge tester behind the Ross lens, you work the surface until you obtain a smooth null.

Telescope Making, Book 3. The horizontal axis is labeled with the values of the ratio F/F'. F is the focal length of the primary mirror and F' is the focal length of the plano-convex lens. The vertical axis gives B/F' which is the source-to-lens spacing B divided by the lens focal length.

The Ross Null Test allows testing any conic surface, not only paraboloids. Only the lens-to-source and lens-to-mirror spacings must be changed. The first author performed computer ray-trace calculations for mirrors having focal ratios of f/3.5, f/4, f/5, f/6, f/8, and f/10, and eccentricities ranging from 0.70 to 1.50 in steps of 0.05. The eccentricity of a paraboloid is 1.0. Those of ellipsoids are less than 1 and those of hyperboloids are greater than 1. The range from 0.7 to 1.5 covers the normal range of primary mirrors for amateur telescopes.

Null lens focal lengths were computed for each of the above combinations, with mirror-to-lens focal length ratios ranging from 4.0 to 20.0. These combinations produce over 1,700 separate cases, each of which was computer optimized to produce the tables and graphs presented with this article. Nine hours of CPU time on a large mainframe computer was required for the job! Hundreds of additional runs were made to determine the correction factors for null lenses having different thicknesses and refractive indices than the nominal values chosen for our cases.

In the Ross Null Test any departures of the lens thickness or refractive index from the nominal values used in the calculations requires that the thickness and index correction factors be applied to the nominal values given in the graphs. If the actual lens thickness is different from the nominal lens thickness given in Figure 2, a correction factor must be applied to the nominal B/F' value.

Because the refractive index of optical glass varies with wavelength, you must use a red filter with the light source. We selected BK7 glass as the material for the lens. It has an index of 1.51432 at the red C wavelength used in calculating the curves (656.3nm). The the Ross test, you must use a correction factor if you make the lens from glass other than BK7. We have calculated correction curves to enable you to do this. More on this point later.

The lens thickness is an important parameter in setting up the test because we chose to use the plano-convex lens with its convex side facing the mirror. This orientation is preferable because it is less sensitive to alignment errors and thus easier to set up. We adopted a lens thickness of 0.300 inches and all the calculations were performed with this thickness. (In the Dall null test, since the plano side faces the mirror, the lens thickness has very little affect on the computed B/F' values.)

Because our nominal calculations are based on a 20-inch diameter mirror, the nominal lens thickness scales with the mirror diameter. This means that the test lens for a 10-inch diameter mirror would be 0.150 inches. This also means that the computed B/F' values for a 20-inch mirror with a 0.300-inch lens thickness will be identical with a 10-inch mirror and a 0.150-inch lens thickness; that is, the spacing and thickness dimensions all scale linearly relative to the nominal mirror diameter of 20-inch. Figure 2 plots this linear "nominal" lens thickness relationship for other mirror diameters. We discuss this correction further in Example 2.

To determine the correct B/F' spacing for a conic mirror, select the graph for the mirror's focal ratio and then interpolate between the two adjacent curves to find the B/F' value corresponding to the eccentricity of the mirror. If the focal ratio is in between those curves graphed, then double interpolation is necessary.

To assist the telescope maker in understanding actual applications of the Ross Null Test we have worked out four numerical examples. Example 1 is a completely straightforward case you can scale right off the graphs. In example 2, you must apply a correction factor because the null lens in not made of BK7.

Example 3 shows how to test the hyperboloidal primary of a Ritchey-Chretien system using a lens of nominal thickness and material. Finally, example 4 shows how to correct for a null lens of a different thickness.

Practical aspects of implementing the Ross Null Test are discussed following the examples.

Example 1 *You wish to test 10-inch f/4 paraboloidal primary mirror with a 4-inch focal length BK7 lens of 0.150-inch thickness.*

Because the lens is made from BK7, no index correction factor is needed. From Figure 9, you can see that

Paraboloid D/F' Values

F/F'	f/3.5	f/4.0	f/5.0	f/6.0	f/8.0	f/10.0
4.0	6.759267	6.755842	6.752081	6.750240	6.748688	6.748149
5.0	8.661490	8.657204	8.652496	8.650195	8.648247	8.647571
6.0	10.579312	10.574167	10.568519	10.565752	10.563409	10.562593
7.0	12.508234	12.502231	12.495645	12.492419	12.489672	12.488729
8.0	14.445478	14.438622	14.431096	14.427406	14.424280	14.423184
9.0	16.389210	16.381496	16.373035	16.368887	16.365358	16.364125
10.0	18.338143	18.329577	18.320180	18.315573	18.311661	18.310291
11.0	20.291353	20.281933	20.271604	20.266541	20.262232	20.260719
12.0	22.248137	22.237865	22.226608	22.221089	22.216389	22.214751
13.0	24.207965	24.196845	24.184658	24.178684	24.173599	24.171812
14.0	-26.170413	26.158443	26.145326	26.138905	26.133425	26.131517
15.0	-28.135144	28.122330	28.108286	28.101408	28.095565	28.093507
16.0	-30.101887	30.088223	30.073257	30.065926	30.059692	30.057500
17.0	-32.070406	32.055898	32.040009	32.032226	32.025606	32.023272
18.0	-34.040521	34.025159	34.008358	34.000125	33.993127	33.990667
19.0	-36.012064	35.995864	35.978133	35.969460	35.962085	35.959471
20.0	-37.984907	37.967857	37.949213	37.940089	37.932343	37.929590

Note: The optical path difference for the Ross Null Test exceeds 1/4 wave for D/F' values listed as negative in the table. These are in the f/3.5 column for F/F' values between 14 and 20.

Table 1: Nominal D/F' Values for Paraboloids

the nominal lens thickness is 0.150 inches, the same as the lens in this example. No thickness correction factor is needed. The F/F' ratio is 40/4 = 10.

By looking on the f/4 curve in Figure 2, you will see that for F/F' = 10, the B/F' value is 0.6008. Thus, the source-to-lens separation, B, is 0.6008·F' = 2.4032 inches. You would simply set this distance between the plano lens surface and the source, and the adjust the spacing between the lens and the mirror until the return beam was focused on the knife edge or Ronchi grating. Remember that the lens must be moved with the source/knife edge as a unit. This entire assembly is shifted as a whole relative to the mirror.

Alternatively, it is convenient, at times, to set the nominal spacing between the lens and mirror, and then adjust the spacing between the lens and source. In fact, for those telescope makers not having a precise method of setting the lens-to-source spacing (B) to an accuracy of better than 0.005 inches, it is advisable, and easier, to set the mirror-to-lens spacing (D) as accurately as possible (to better than 1 millimeter) and adjust the lens-to-source distance by moving the tester alone until it is at the focus of the set up. A wooden spacer, about 1 inch square with tapered ends cut and filed to the required length, within a millimeter works well in practice.

To assist in this alternate approach to setting up the Ross Null Test, we compiled D/F' values that are given in Table 1. For a given situation, you would interpolate between values listed in Table 1.

Because of the large range of D/F' values, plots of D/F' curves done in the same manner as the B/F' values

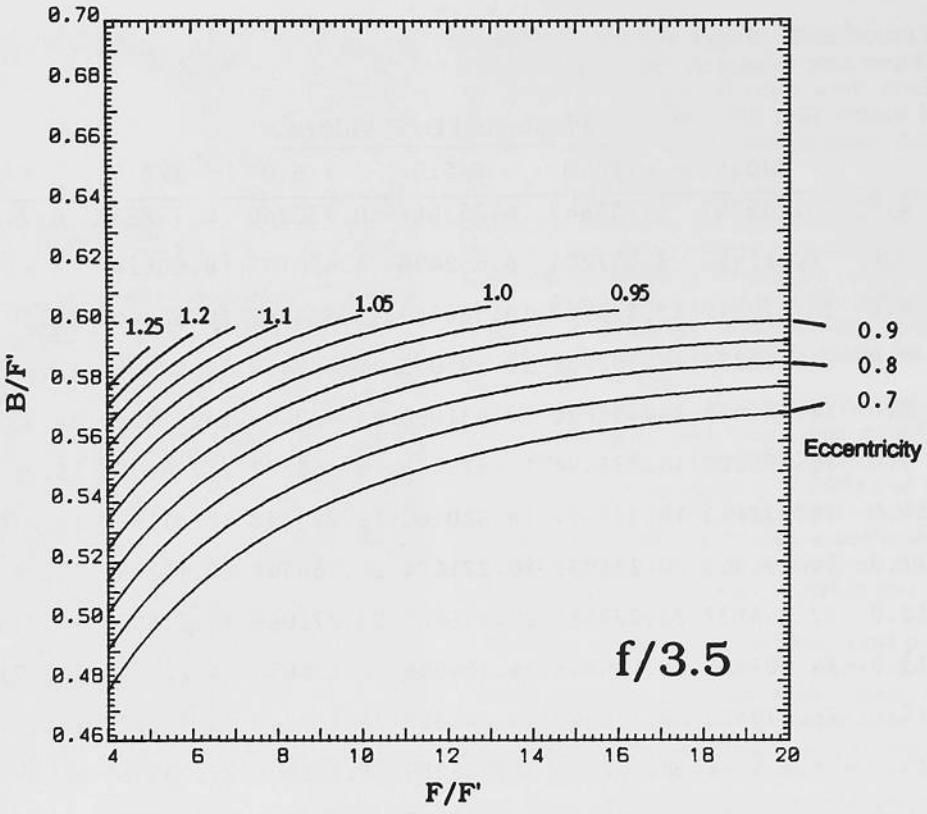


Figure 3: Ross Null Test for Conic Sections, f/3.5

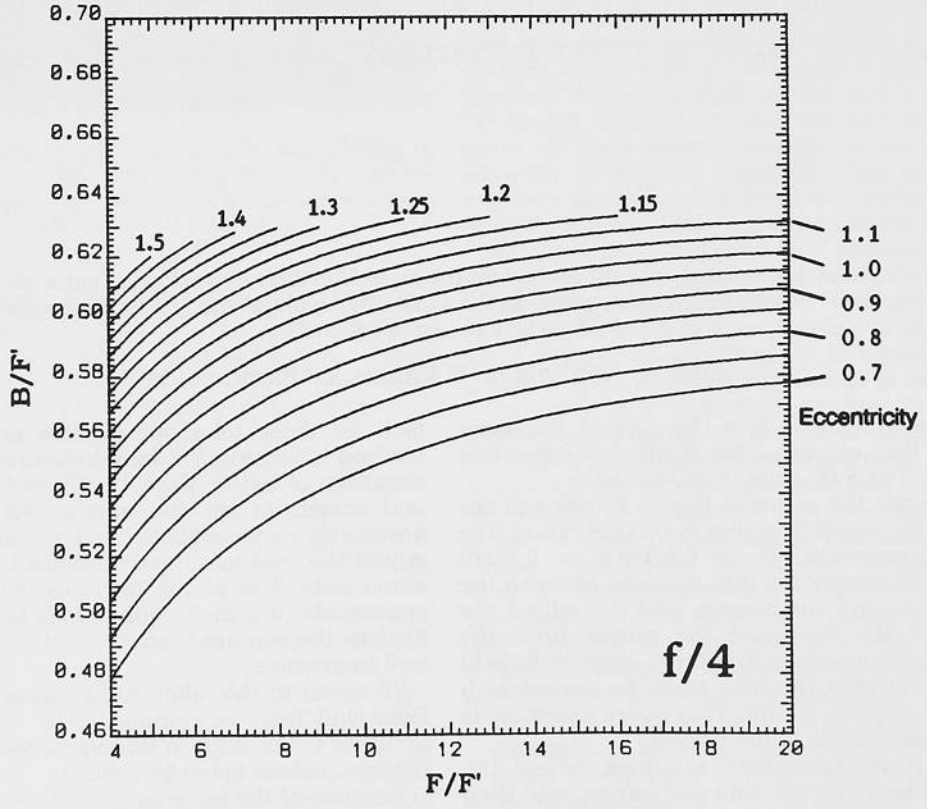


Figure 4: Ross Null Test for Conic Sections, f/4.0

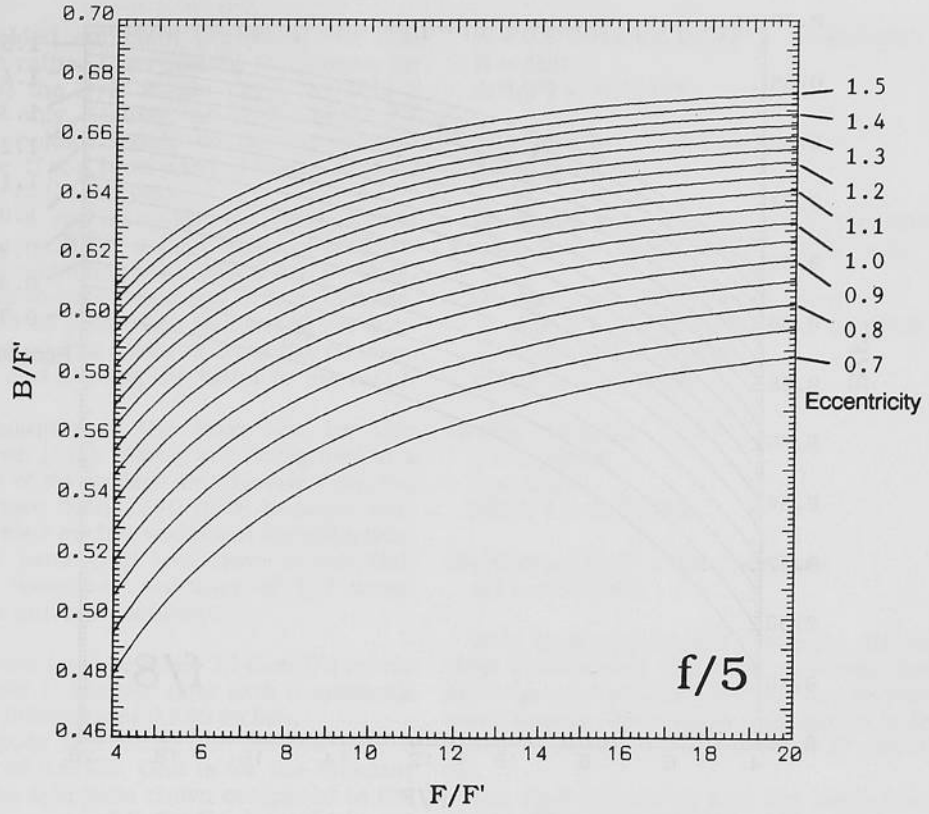


Figure 5: Ross Null Test for Conic Sections, f/5.0

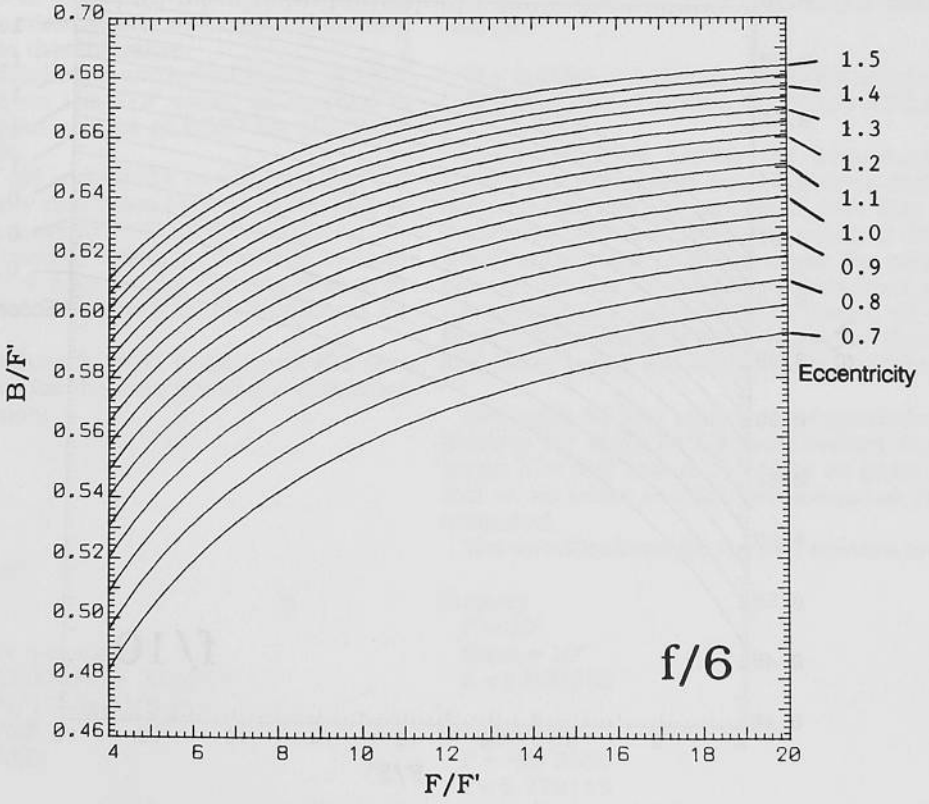


Figure 6: Ross Null Test for Conic Sections, f/6.0

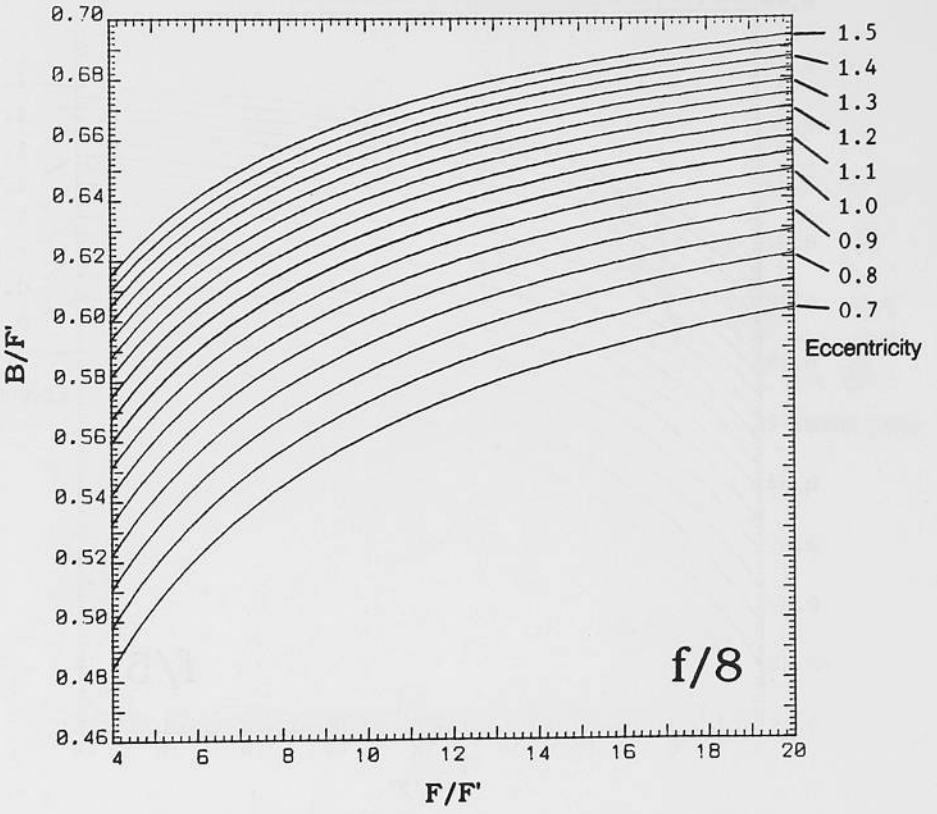


Figure 7: Ross Null Test for Conic Sections, f/8.0

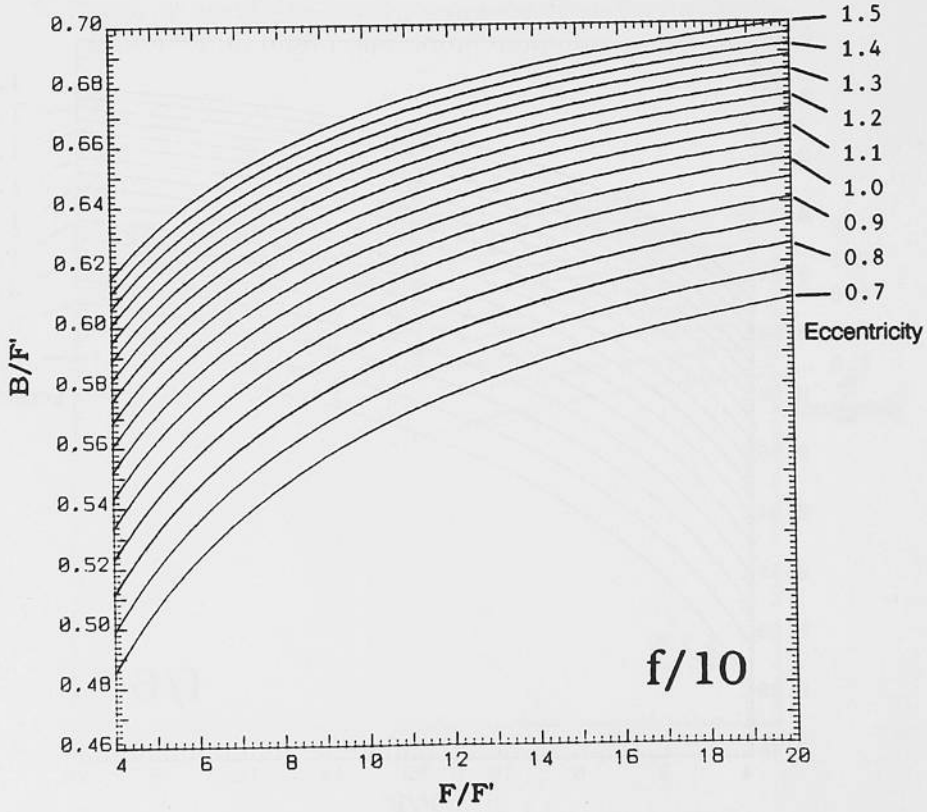


Figure 8: Ross Null Test for Conic Sections, f/10.0

would not have yielded sufficient precision. For this reason, we tabulate rather than plotted the values for D/F'. Note, too, that the D/F' values given in Table 1 are for paraboloids only. Listing the D/F' values for ellipsoids and hyperboloids would be far too voluminous to include here. If you have need of these, we suggest you contact one of the authors.

Referring to Table 1, matching the f/4 column with the F/F' = 10.0 row results in a D/F' value of 18.3296 for this example. Multiplying this value by F' (4.00 inches) gives the lens-to-mirror spacing of D = 73.3184. The Ross setup could be performed by placing the convex vertex of the lens at this distance from the concave vertex of the mirror and moving the tester to the resultant focus.

The wavefront accuracy of the Ross test for this example is 1/20 wave. If the mirror can be figured to a perfect null, no part of its surface will deviate from the ideal parabola by more than 1/40 wave because surface defects are doubled on the wavefront by reflection. By comparison, the same null lens used in the Dall arrangement has a wavefront accuracy of 1/7 wave, yielding a 1/14 wave surface accuracy.

Example 2 *You now test the same 10-inch f/4 mirror as you did in example 1, but this time with a spectacle crown lens having a thickness of 0.250 inches.*

You now must apply two correction factors to the nominal B/F' value of 0.6008. One is for the different refractive index of the spectacle crown compared to the nominal BK7, and the second is for the lens thickness of 0.250 inches.

Spectacle crown glass has a refractive index at the C-line (656.3nm) of 1.52036 compared to 1.51432 for BK7. The difference, ΔN, is thus 0.00604. Due to the non-linear nature of the index correction factor, the maximum difference in refractive index from BK7 lie within 0.03 of the nominal value, so present difference 0.00604 is well within this tolerance.

Use Figure 10 to obtain the correction factor Δ(B/F'). From the value 10.0 on the F/F' scale, go upward to the f/4 curve, then read a value of 0.027 for Δ(B/F')ΔN from the vertical scale.

Multiply 0.027 by ΔN = 0.00604 to obtain Δ(B/F') = 0.00016. Now, multiply this value by F' (4.00 inches) to obtain the correction factor to B of ΔB = 0.00064.

Figure 11 can be used in a similar manner to compute the correction factor ΔD for the spacing change in D. The resulting value for Δ(D/F') is -0.00042 and for ΔD is -0.00168.

The following procedure is used to compute the correction factor required for the lens thickness departure from nominal dimension:

Given:
F/F' = 10
e = 1.0 (parabola)
TH(lens) = 0.250"
DIAM(mirror) = 10.0"
f# = 4.0

Calculate the auxiliary quantities:
Q = (((F/F')-12)/8)·(0.00492) + 0.00714
R = 0.000178·((F/F')/12)·((e-1)/0.3)
S = 3-((200·TH)/DIAM)
Δ(B/F') = (5/f#)(Q+R)(S)

For this example:
Q = 0.00591
R = 0.0 (because mirror is a parabola)
S = -2.0
Δ(B/F') = -0.01478

Multiplying by F' = 4.0 you obtain:
ΔB = -0.05912.

Similarly, you could compute the equivalent ΔD correction factor from following procedure:

Calculate the auxiliary quantities:
T = (((F/F')-12)/8)·(0.00387) + 0.00603
S = 3-((200·TH)/DIAM)
Δ(D/F') = (5·T·S/f#)

In this example:
T = 0.00506
S = -2.0
Δ(D/F') = –0.01256

Multiplying by F' = 4.0 gives you:
ΔD = –0.05060

Note that you cannot compute ΔD for conics other than paraboloids (there is no eccentricity term in the above procedure), but that ΔB can be calculated for any conic mirror. Once again, this is due to the impracticality of tabulating all the data for D and ΔD in this article.

The final step is to add the correction terms (ΔB or ΔD) to the nominal values of B and D:

B = B(nominal) + ΔB(index) + ΔB(TH)
D = D(nominal) + ΔD(index) + ΔD(TH)

In this example, you use the previously obtained values for B(nominal) and D(nominal) from Example 1, and get:

B = 2.4032 – 0.05912 + 0.00064 = 2.3447
D = 73.3184 – 0.05060 – 0.00168 = 73.2661

Thus by either setting the lens-to-mirror distance using D or setting the source-to-lens distance using B, the null test can be performed with this lens which is somewhat different from the nominal BK7 lens. It is worth noting that in this example the correction factors amount to only an additional wavefront error of 1/500 wave in setting the correct spacings. Of course, wavefront differences will not always be this small; larger and faster optics will show much greater discrepancies.

Example 3 *You now test a hyperboloid 10-inch f/4 primary for an f/10 Ritchey-Chretien Cassegrain telescope. The null lens is the same as given in Example 1, that is, no index or thickness correction factors need be computed.*

The specifications for the two mirrors are:

Primary
F = 40"
diam = 10"
e = 1.082732

Secondary
F = –23.3333"
e = 2.779145
magnification = 2.5

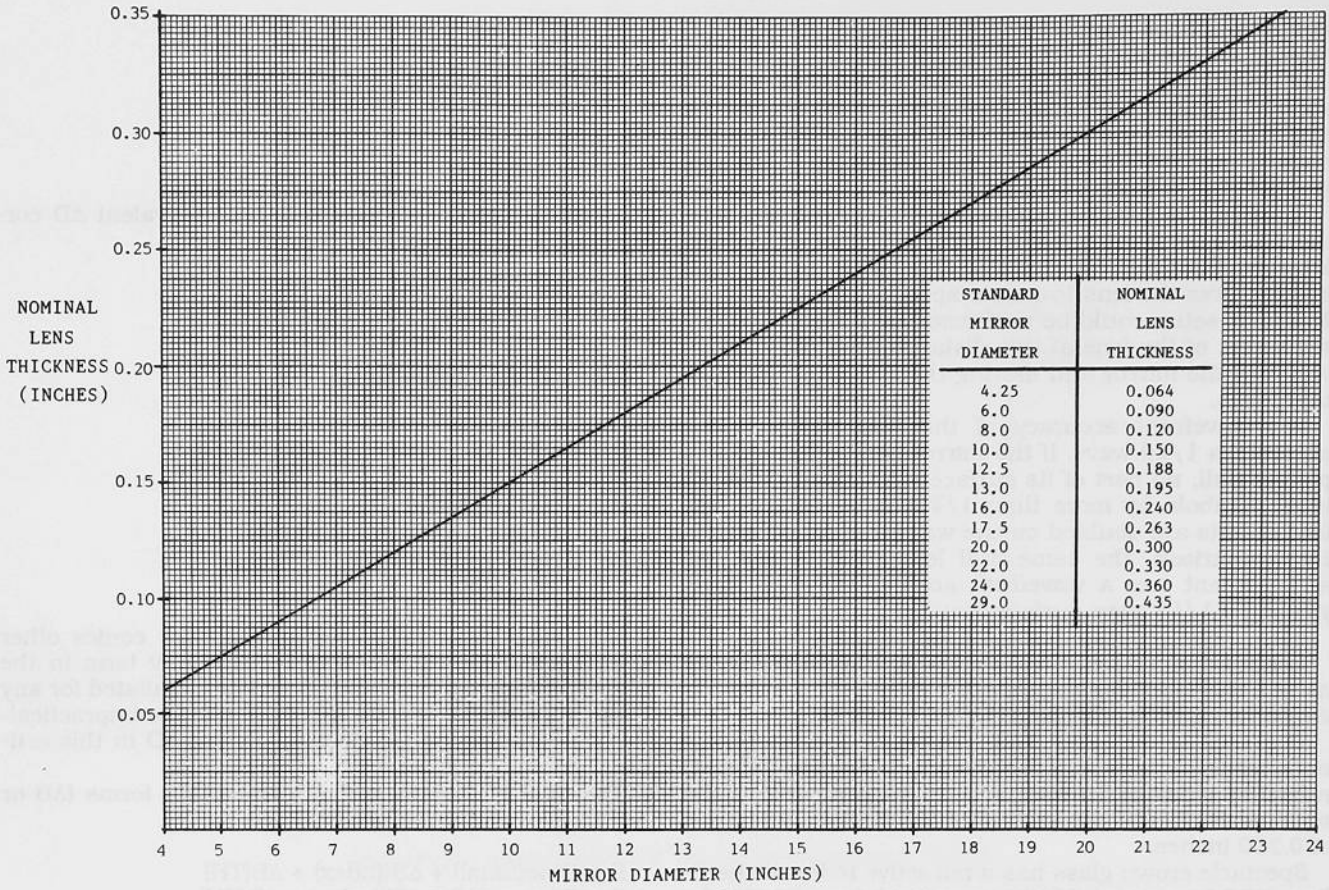


Figure 9: Nominal Thickness for the Ross Null Lens

In this example we assume the null lens is the same as given in Example 1, that is, you will not have to compute index or thickness correction factors. Because the primary is not a parabola, but a hyperbola (e = 1.08273), you must use Figure 4, for f/4 mirrors, to obtain the appropriate B/F' value.

The primary's eccentricity lies between the e = 1.05 and e = 1.10 curves of Figure 4, so you interpolate between these two, along the F/F' = 10.0 line, to obtain the value of B/F' = 0.6113. Multiply by F' = 4.0 to get B = 2.4452.

When you set up the test, set the lens-to-source distance at 2.4452 inches and vary the mirror-to-lens separation until the beam reaches the knife-edge or grating. (Please note that in this article we do not give equivalent D/F' values for mirrors other than parabolas.)

In this example, the residual wavefront error of the Ross Null Test is only 1/16 wave for a perfect mirror. The difference between the hyperboloidal primary of the example and a paraboloidal mirror is 0.7 waves. A paraboloid would give a very poor null at this setting.

Example 4 *You wish to null test the same 10-inch f/4 hyperboloidal primary as in Example 3, but this time with a BK7 null lens having a thickness of 0.250 inches.*

The only difference between this example and Example 3 is that the null lens is not the nominal thickness. Thus, just as you did in Example 2, you must compute the correction factor Δ(B/F') for the actual lens thickness and add this to the nominal B/F' value determined in Example 3.

Given:

F/F' = 10
e = 1.08273
TH(lens) = 0.250"
DIAM(mirror) = 10.0"
f# = 4.0

Calculate:
Q = 0.00591
R = 0.000041
S = -2.0
Δ(B/F') = -0.01488

Multiplying by F' = 4.0 gives you:
B = -0.0595

The final step is to add the correction term ΔB to the nominal value for B from example 3:
B = B(nominal) + ΔB(TH)
B = 2.4452 - 0.0595 = 2.3857

For this slightly thicker lens, the lens-to-source distance would be set to 2.3857 inches (about 1/16-inch closer than the nominal null lens is set) and then you would vary the mirror-to-lens separation (moving the tester and lens as a unit) until the return beam reaches the focus.

Selecting the Lens The accuracy obtained with the Ross Null Test is determined by the focal length of the lens relative to the mirror; that is, as the F/F' values increase, the quality of the null decreases. The longer the focal length of the lens the more accurate the null and the farther it will be from the tester. Consequently the lens must be large to handle the light cone.

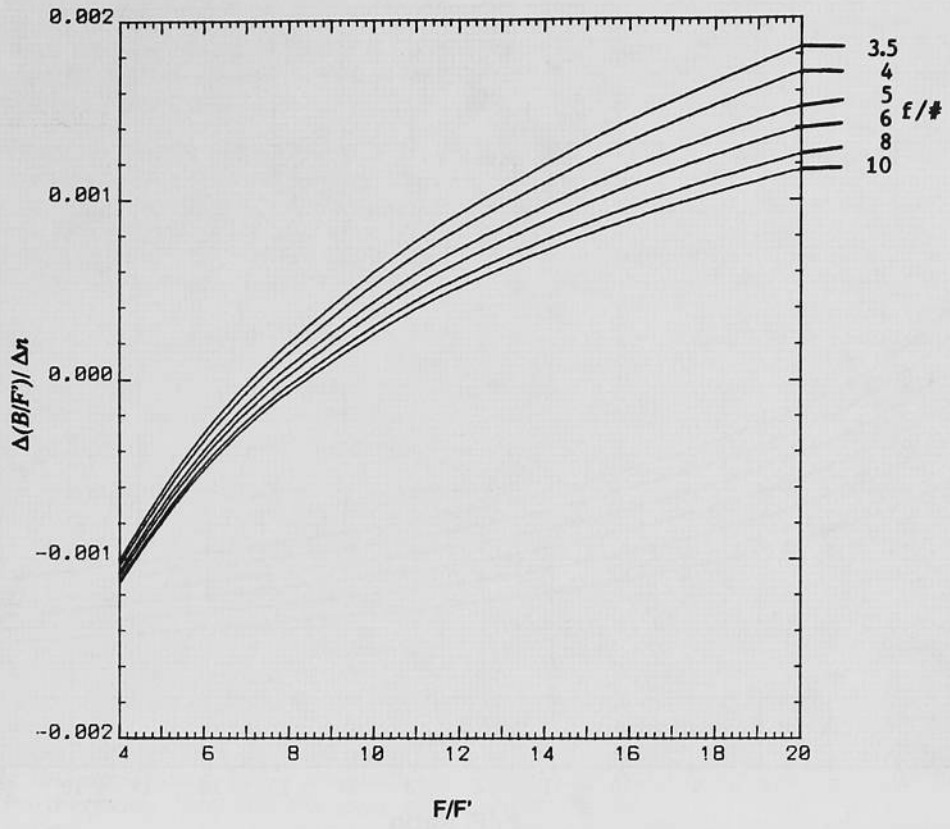


Figure 10: Δ(B/F')/Δn Correction Factor for Refractive Index

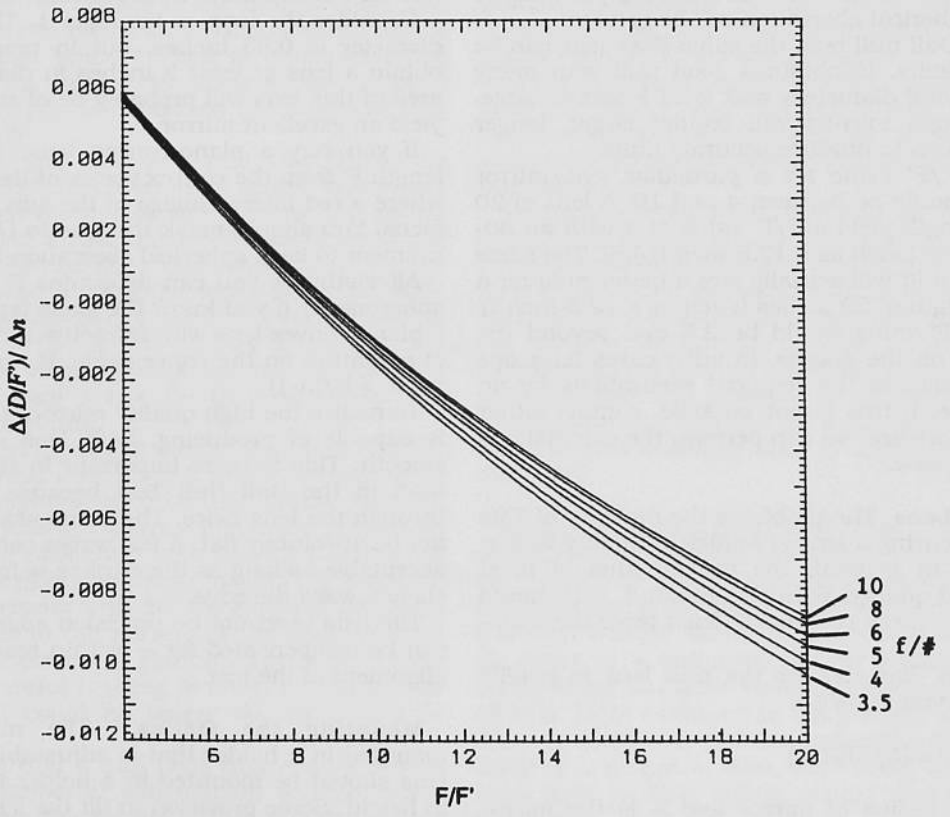


Figure 11: Δ(D/F')/Δn Correction Factor for Refractive Index

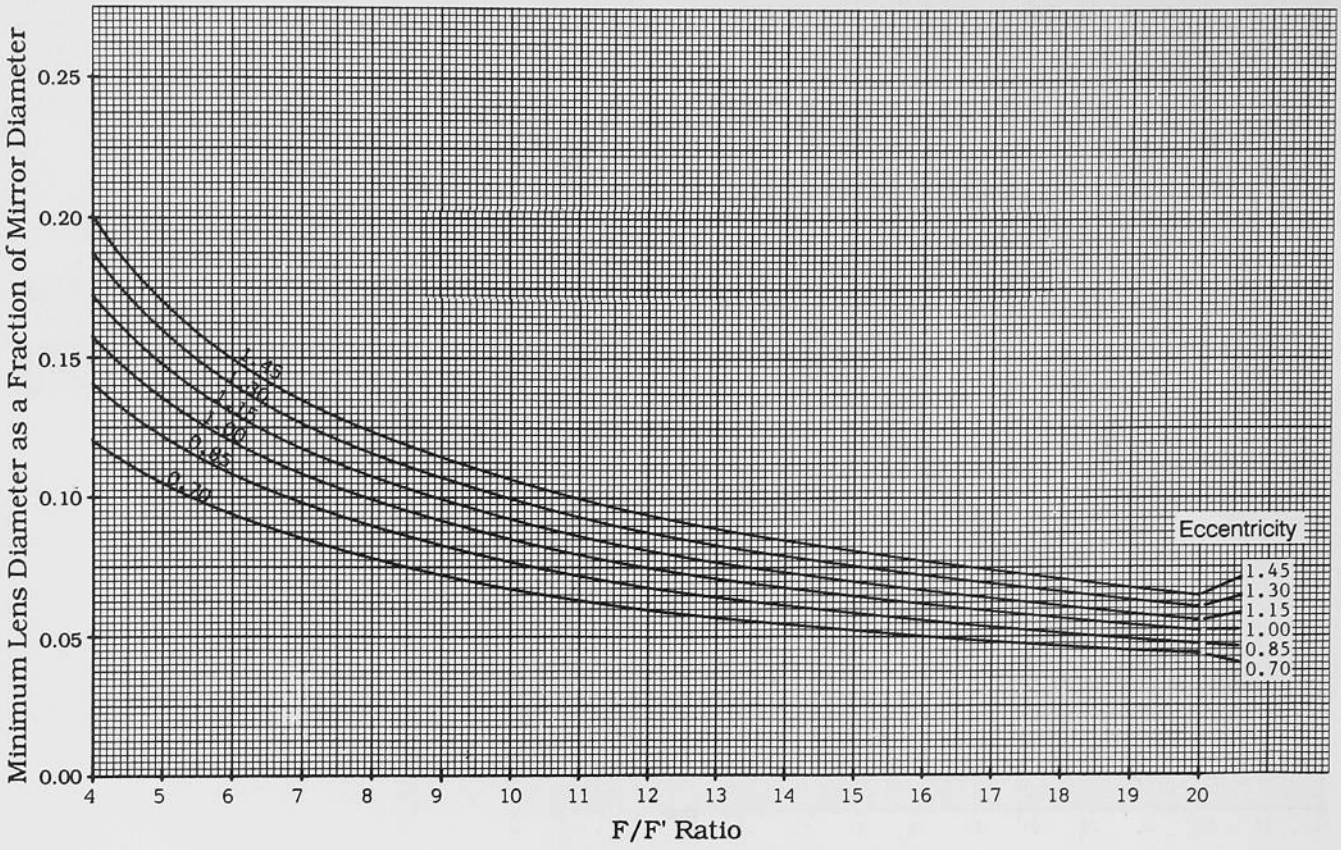


Figure 12: Minimum Lens Diameters for the Ross Null Test

Although small, relatively inexpensive lenses can be used, the quality of the null will not be good because the residual spherical aberration will be greater.

As with the Dall null test, the same Ross lens can be used, within limits, to obtain a good null with many mirrors of varying diameters and focal lengths. Large, short focal length mirrors will require larger, longer focal length lenses to produce accurate nulls.

Ideally the F/F' value for a particular lens/mirror combination should be between 4 and 10. A lens of 20 inches focal length yield a F/F' value of 4 with an 80-inch focus mirror (such as a 17.5-inch f/4.5). The same lens is also ideal (it will actually give a better null) for a mirror focal length of 50 inches (such as a 12.5-inch f/4), but the F/F' value would be 2.5 and beyond the range imposed on the graphs. In such cases telescope makers can calculate the required separations by an actual ray trace. If this is not possible, contact either one of the authors and we can perform the calculations for your special case.

Obtaining a Lens The problems the majority of TMs will have is procuring a lens of sufficient quality to perform the test. In general, the central area of most lenses is of good quality. With this in mind, you should purchase a mass produced lens at least twice the diameter needed.

The minimum diameter for the null lens is readily calculated once you know D:

Lens Diameter = (A/R)(R-D)

where R is the radius of mirror and A is the mirror diameter. Alternatively, you can use the chart in Figure 12 to determine the lens size when you do not know D, and for mirrors other than paraboloids.

Consider the lens in Example 1. The minimum lens diameter is 0.85 inches, but in practise, you should obtain a lens at least 2 inches in diameter. The active area of this lens will probably be of sufficient quality to yield an excellent mirror.

If you buy a plano-convex lens, measure its focal length F' from the convex vertex of the lens to the point where a red filtered image of the sun comes to a sharp focus. You should mask the lens to f/10 for this measurement to keep spherical aberration to a minimum.

Alternatively, you can determine F' with an accurate spherometer if you know the glass type of the lens. For a plano-convex lens with refractive index, n, and radius of curvature on the convex side, R, the focal length, F', is: F' = R/(n-1)

To realize the high quality mirrors the Ross Null Test is capable of producing, both lens surfaces must be smooth. This is more important in the Ross Null Test than in the Dall Null Test because the light passes through the lens twice. The plano side of the lens need not be absolutely flat. A few waves convex or concave is acceptable as long as the surface is free of zones, especially toward the edge.

The lens need not be precision edged because wedge can be compensated for — within reason — during the alignment of the test.

Mounting the Optics The mirror should be mounted in a holder that is adjustable in tilt. The null lens should be mounted in a holder that is adjustable in height. Some provision to tilt the lens for fine adjustment is also necessary. The null lens and Foucault

tester should be separate units so they can be moved independently on a wooden board, and then the lens/tester positioned as a unit by moving the board. Two tables of identical height are well suited for supporting the mirror stand and lens/tester unit.

Use a Slitless Foucault Tester The slitless version of the Foucault tester is the preferred configuration since it keeps the source and knife edge close together without the need of a beam splitter. The unit should be mounted so it can be adjusted in height as well as the standard left to right and forward and backward motions.

The second author's tester, shown in the photographs, is built around a microscope stage. The three degrees of motion have made alignment of the test a painless and quick exercise. The TM should mount the slitless tester on an eyepiece focusing mount to provide the necessary adjustment in height.

If the light source in the Foucault tester is a tungsten lamp, it must be filtered to reduce the effects of chromatic aberration. Chromatic aberration is worse in the Ross test than in the Dall test because the light makes a double pass through the lens. Fit a deep red filter such as an over-the-lens photographic filter large enough to cover the source and the return beam. Double filtering reduces the chromatic effects which can be bothersome when the knife edge is set at the null position of a fast mirror.

Alternatively, a bright red LED is virtaully ideal for the light source for this application. LEDs are relatively monochromatic. Furthermore, they are compact and their heat output is low.

Setting up the Test Before you set up the test, you must know the radius of the mirror within a millimeter. Even a small difference between the real and optimum value can degrade the quality of the null in large, fast mirrors. Remember to recheck the radius of the mirror after the figure has been roughed in. Most telescope makers deepen the center to achieve the required parabola, and this process shortens the radius of curvature substantially.

I must caution you that any null test should be applied carefully. Let me illustrate. A couple years ago I figured a 12.5-inch f/4 mirror with a Ross null set-up that, I thought, had a residual 1/40th-wave wavefront error. When I performed the calculations to set up the test, however, I used a refractive index for yellow light instead of the deep red light I used in testing. I used a nominal mirror radius of 100 inches instead of the actual 99.84-inch radius. I figured the mirror with above technique until I saw no trace of zones and achieved an excellent null.

When I rechecked my calculations I discovered, to my dismay, the spherical aberration introduced resulted in a 1/14-wave undercorrection on the mirror surface. Reoptimizing the lens spacing for minimum aberration (1/40-wave on the wavefront) with red light and using the mirrors actual radius required moving the null lens (3.5 inches in diameter and 20 inches focal length) a quarter-inch closer to the mirror. In the optimized set up, the 1/14-wave error was glaringly apparent. It took another hour of careful figuring to clean up the null to the point where I could no longer see any zones or undercorrection.

Another point is that if null tests that employ lenses are not aligned properly, astigmatism will be introduced. If you know the mirror is free of astigmatism from examining the image of a very small pinhole at the centre of curvature with a high power eyepiece, you can safely ignore small astigmatic effects you see during testing. For final testing, of course, every effort should be made to align the null test as accurately as possible.

Set up itself is simple. The separation of the lens and mirror (the D value), is set making sure the axes of the lens and mirror are at the same height. In some instances, it will be easier to use the B spacing to set up the test. Use a machined rod accurate to 0.005 inches in length to set the spacing.

The mirror, as seen through the lens from the tester, must be centered in the lens. If does not appear centered, the lens should be adjusted in height and the lens and tester moved moved left and right as a unit by moving their board until it is. At this point the set up should be aligned well enough that the light from the tester source is reflected back to the knife edge.

After the initial set up, double check everything including the orientation and spacing of the lens. The convex side of the lens must face the mirror, and the B spacing is measured from the plano side to the light source.

Initial set up and alignment will be easier to accomplish if you use a Ronchi grating instead of a knife edge. The effects of poor alignment are more easily seen with a Ronchi screen and can then be corrected. The lens height and tilt is adjusted along with the position of the tester until the Ronchi bands are symmetric. If the mirror has yet to be figured the bands will be curved; they will be straight if the mirror is close to the desired figure.

Alignment will get easier with practice. One thing that will help is that if the mirror stand is well made and if the mirror is placed on the mount in the same orientation, the alignment should be preserved from test session to test session. You can easily switch between the Ronchi and the slit by simply taping the Ronchi grating over the source and knife edge in the Dakin version of the Foucault tester.

In the Ross Null Test the convex side of the lens must face the mirror and the plano side must face the source. The B spacing must be measured from the plano side to the pinhole or slit source. Always check this carefully.

When using the Ross Null Test on a 12.5-inch f/6 mirror, the second author discovered, after many long figuring session in which the surface was tweaked to a level of perfection well past what was practical, that the lens had been inadvertently reversed. The figure turned out to be a wonderfully smooth hyperbola six times deeper than the desired parabola! The mirror had to be reground with fine abrasive to get it back to a sphere. Needless to say this sort of thing only has to happen once. Double-checking both D and B will help you to avoid this.

Hints on Using the Null Test Experience has shown that the Ronchi test with a 100 lines/inch grating is ideal for monitoring the initial stages of figuring. Once the figure is close to that desired, the more sensitive and "cleaner" Foucault test is better for seeing subtle zones in a null test. Ronchi gratings consist of a series of parallel lines etched on glass or photographed on film. Light scattered in the grating, especially if it is dirty or scratched, reduces contrast and thus the visibility of faint zones. Also, the harsh, black and white, lines tend to hide subtle zoning and other forms of roughness.

One lens serves as a test lens for many different mirrors, provided that you calculate new spacings between the mirror, lens, and test unit. In this picture, author-optician Peter Ceravolo null-tests a 16-inch mirror.

Even with the double filtering recommended, chromatic aberration can be troublesome at the null focus of a well figured fast mirror. You will not see extraneous color, but the null will be non-uniform. You will see the center darken when it shouldn't.

This problem can be sidestepped by assessing the mirror's state of correction and smoothness with the knife edge slightly ahead of the null position — just a few thousandths of an inch closer to the mirror — and watching the shadow move in from the right side of the mirror, assuming, fo course, that the knife edge is moving right to left. If the mirror is slightly undercorrected the central area of the mirror will darken first, with the edge following soon after. If the edge darkens first, the mirror is overcorrected. Zonal errors are visible as abrupt changes in light intensity across the face of the mirror if they are severe, or by subtle changes if they are slight. During Ronchi and Knife edge testing, the test should be performed as close to focus as possible for the maximum sensitivity.

In the final stages of testing, you will not need to move the knife edge very much. A slight pressure on the tester is all that is required to cut the beam with the knife edge. Remember that the desired paraboloid or conic will look just like a sphere does in the standard Foucault test.

Know When to Quit At this point a word of caution seems in order: Null tests can be extremely frustrating. Optical testing is a lot like deep sky observing, the more you do it, the more you can see. With the Ross Null Test, an experienced eye can detect subtle zones and other irregularities that will have little or no visible effect on star images.

One factor is crucial in deciding whether a mirror is finished or not: Is the surface smooth, especially the edge? The area of the mirror from the 70% zone to the edge is far more important than the area inside the 70% zone. A slight hill or hollow in the central area of the mirror is acceptable as long as the edge is smooth and well corrected. Slight undercorrection is usually acceptable, but an overcorrected edge should be fixed because it causes an unacceptable haziness in images. Be careful not to push your luck when you bring a mirrors figure close the limit of the test. One wrong move during that last bit of polishing needed to bring the mirror to a state of perfection can set you back hours.

The experienced mirror maker can easily see a 1/20-wave figure error with a Ross null lens large enough to produce a near perfect null. But we do not wish to mislead the tyro into thinking that such precision optics can be achieved simply because one is using a test capable of detecting such errors. The Ross Null Test is simply a tool. Excellent optics are achieved as a result of good technique, practice and patience.

The second author has used a 3.5-inch diameter lens of 20-inch focal length to aid in figuring a 16-inch f/5 and a 14-inch f/4 mirror, as well as a dozen or so smaller mirrors. These mirrors have proved to be excellent performers. The smooth, highly corrected surfaces seen in the Ross Null Test yield high contrast views of the planets as well as crisp star images.

The authors wish to thank Richard Solstad who transformed reams of numbers we generated into the graphs in this article, and Randy Pakan for extensive photographic work.

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High-Finesse Figuring

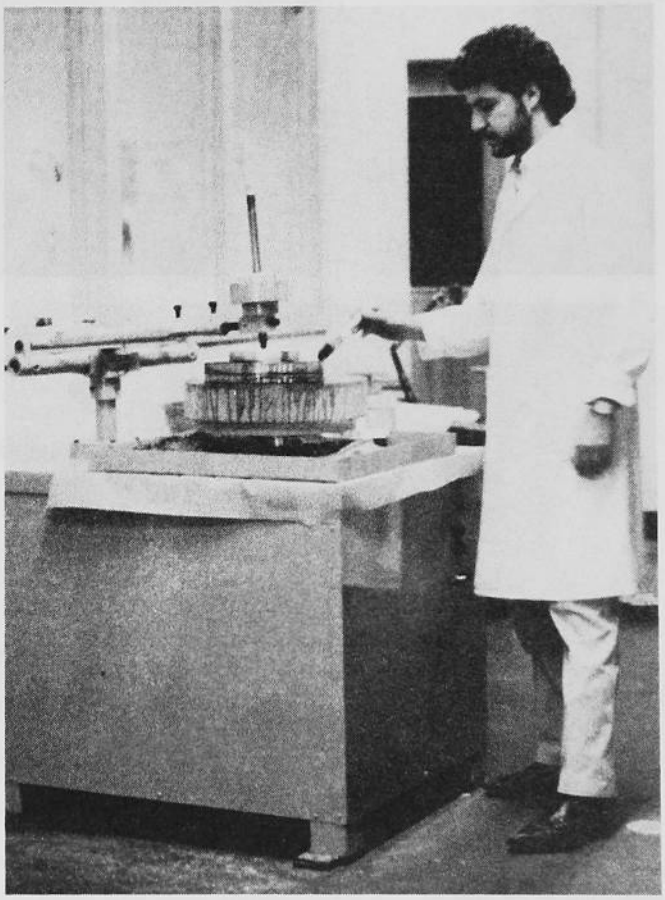
Figuring is the process of tranforming a spherical surface that occurs more or less naturally during the polishing stage into an accurate paraboloid. So deep is the fear that figuring strikes into the hearts of amateur telescope makers that complex catadioptric designs that employ spherical mirrors with correcting lenses, appear regularly in *Telescope Making*.

Yet it is far more difficult and labor intensive to make a good Newtonian-type catadioptric instrument than it is to make an excellent paraboloid in the aperture than TMs usually attempt. Lens making is hardly easy for the average TM because it requires special equipment, and collimation of the completed instrument is even more critical than in the standard Newtonian. Catadioptric systems only come into their own for compact instruments designed around an f/2 primary; in that regime, the only practical figure is a sphere.

This article details a figuring method that, in combination with autocollimation or the Ross Null Test, yeilds fully corrected and smooth paraboloidal surfaces for mirrors like the 16-inch f/5 Pyrex mirror pictured in this article. This 3.2-inch-thick, 50-pound monster is now used by the members of the North York Astronomical Association of Toronto, Ontario.

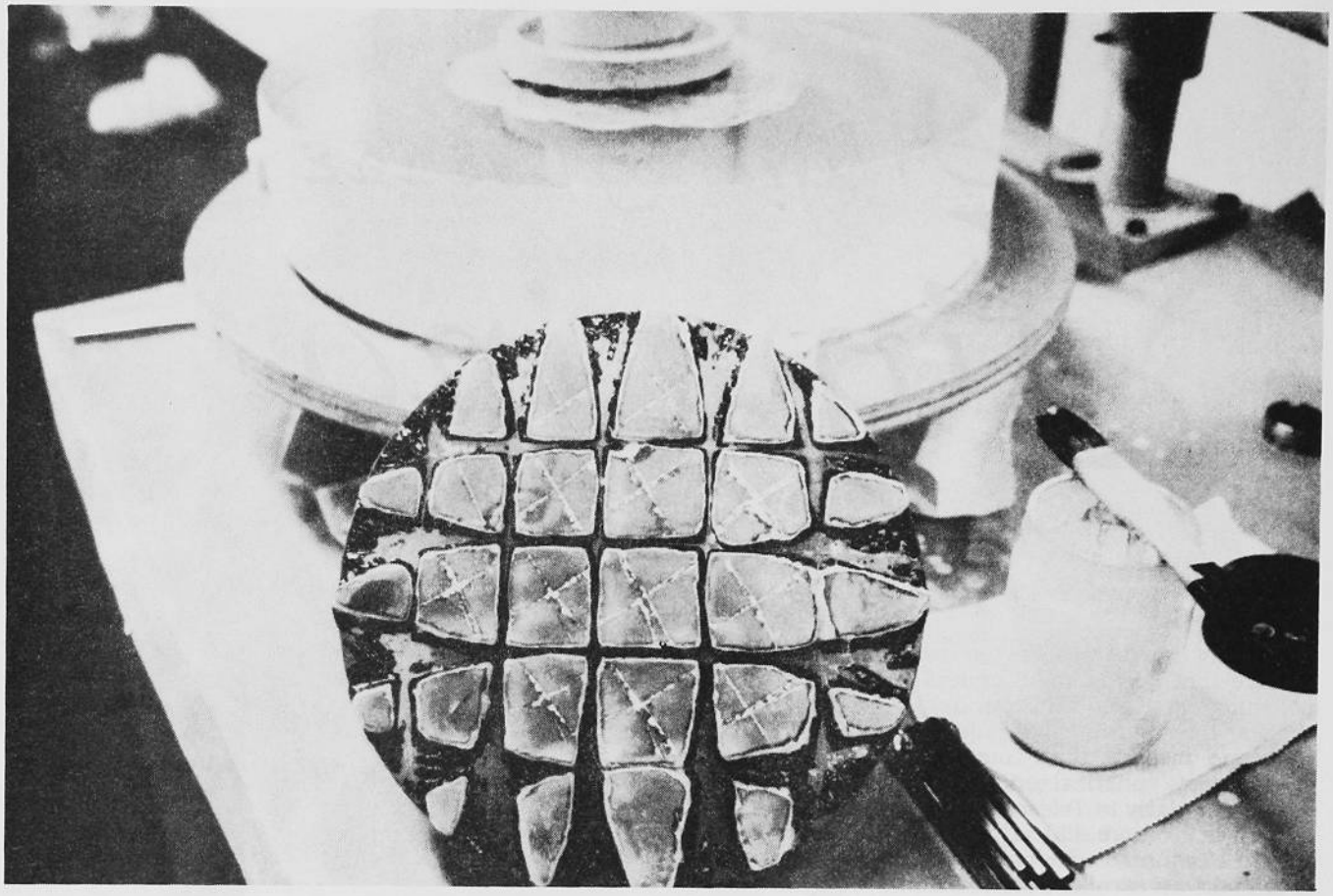
After spending uncountable hours in the basement pushing glass by hand and walking around barrels as a teenage Telescope Nut, I completed an optical apprenticeship at a professional optical shop. Now, years later, I am totally spoiled and do nearly all my work by machine. Although I mention machine work in this article, I still do figuring by hand on a very slowly rotating spindle. TMs who do not use machines can still apply the technique since a machine only mimics the motions the optician working by hand would make. In fact, I first started using this technique without a machine.

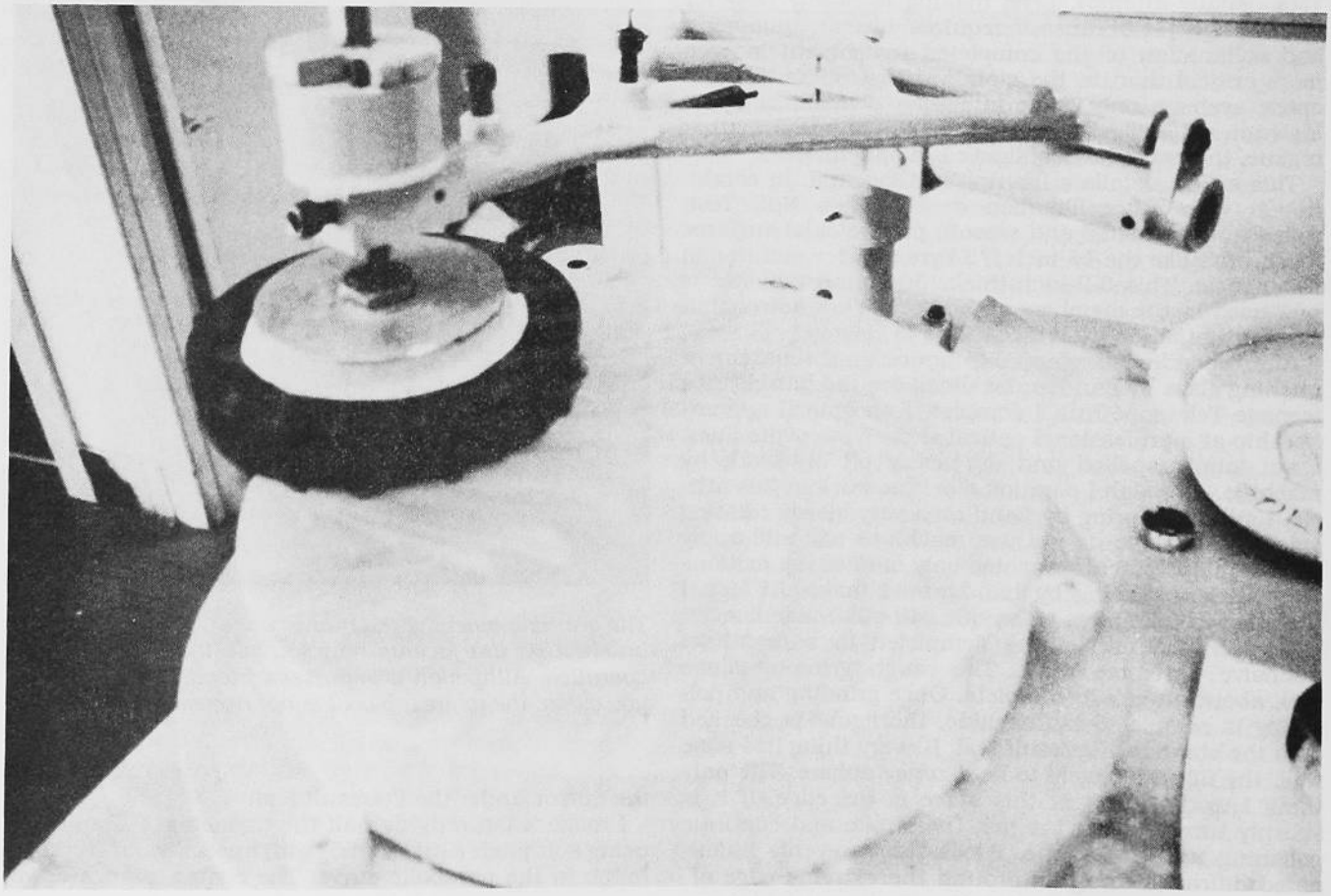
The 16-inch mirror was completed in a month of intensive part-time work. The rough grinding alone took about a week to complete. Once grinding and polishing is completed by machine, the figure is checked with the standard Foucault test. If every thing has gone well, the figure is likely to be a zoney sphere. The only thing I worry about at this stage is the edge. If it is sharply turned down I adjust the stroke and continue polishing until it is gone. I look for an evenly illuminated diffraction ring all around the extreme edge of the mirror under the Foucault test.

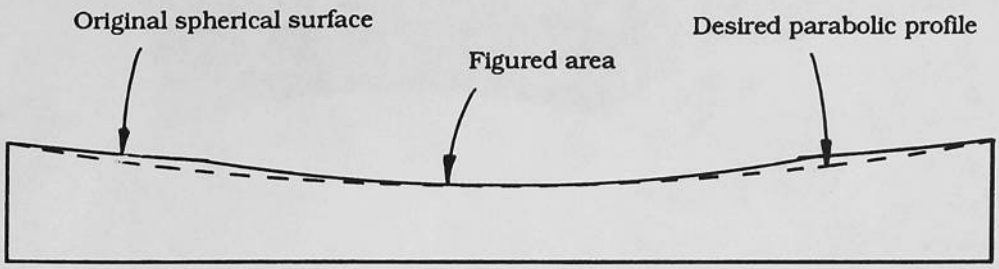


The grinding machine the author uses. Abrasive slurry is brushed on the face-up mirror while the machine is in operation. Althpough it impresses friends and will keep you clean, the white lab coat is not necessary.

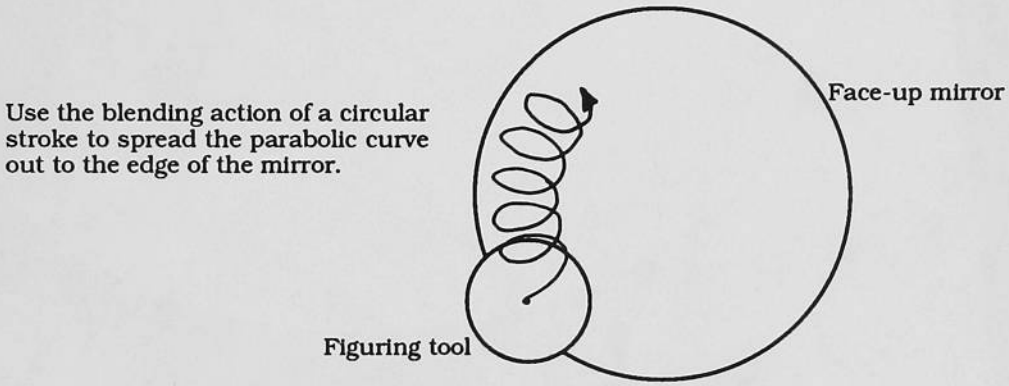
I make a lap roughly half the diameter of the mirror using soft pitch (Gugolz #55) with specially cut facets to rough in the parabolic curve. The center is worn down







A partially figured mirror looks as if it has a turned-down ege. This is because a turned-down edge has a longer radius than the central region, and the central "figured" region of the mirror has a shorter radius than the outer, largely untouched, region. The correction must be spread to the edge.



For figuring, the machine is set up with a half-diameter lap. The lap has specially cut facets so that the lap's polishing action is concentrated toward the center. Tracks left by the polishing compound show where the stroke ends. At lower left, the parabolic curve is being spread toward the edge of the mirror. For hand figuring, the arm is swung aside and a small tool guided by the optician.

Figuring is the process of tranforming a spherical surface that occurs more or less naturally during the polishing stage into an accurate paraboloid. So deep is the fear that figuring strikes into the hearts of amateur telescope makers that complex catadioptric designs that employ spherical mirrors with correcting lenses, appear regularly in *Telescope Making*.

Yet it is far more difficult and labor intensive to make a good Newtonian-type catadioptric instrument than it is to make an excellent paraboloid in the aperture than TMs usually attempt. Lens making is hardly easy for the average TM because it requires special equipment, and collimation of the completed instrument is even more critical than in the standard Newtonian. Catadioptric systems only come into their own for compact instruments designed around an f/2 primary; in that regime, the only practical figure is a sphere.

This article details a figuring method that, in combination with autocollimation or the Ross Null Test, yeilds fully corrected and smooth paraboloidal surfaces for mirrors like the 16-inch f/5 Pyrex mirror pictured in this article. This 3.2-inch-thick, 50-pound monster is now used by the members of the North York Astronomical Association of Toronto, Ontario.

After spending uncountable hours in the basement pushing glass by hand and walking around barrels as a teenage Telescope Nut, I completed an optical apprenticeship at a professional optical shop. Now, years later, I am totally spoiled and do nearly all my work by machine. Although I mention machine work in this article, I still do figuring by hand on a very slowly rotating spindle. TMs who do not use machines can still apply the technique since a machine only mimics the motions the optician working by hand would make. In fact, I first started using this technique without a machine.

The 16-inch mirror was completed in a month of intensive part-time work. The rough grinding alone took about a week to complete. Once grinding and polishing is completed by machine, the figure is checked with the standard Foucault test. If every thing has gone well, the figure is likely to be a zoney sphere. The only thing I worry about at this stage is the edge. If it is sharply turned down I adjust the stroke and continue polishing until it is gone. I look for an evenly illuminated diffraction ring all around the extreme edge of the mirror under the Foucault test.

I make a lap roughly half the diameter of the mirror using soft pitch (Gugolz #55) with specially cut facets to rough in the parabolic curve. The center is worn down by center-over-center strokes with no overhang. If the mirror is large and fast, this technique will only put a wide depression in the mirror. This is illustrated in figure 1.

As the work progresses, the stroke is shortened considerably and offset so that the center of the stroke lies as close as possible to the edge of the mirror without fear of the lap tipping off the edge. This will broaden the hole into a rough parabola. Because working the edge tends to undercorrect the mirror, you have to

Hold the hand-figuring tool with the index finger pointing toward the center of the mirror and applying pressure. This helps keep the lap, whose center is almost always over the edge of the mirror, from tipping over.

work the edge and the centre alternately to maintain the desired correction.

If the mirror is f/5 or slower, this technique alone is capable of producing mirrors of pedestrian quality, equivalent to some of the inexpensive but too-often mediocre commercial optics I have tested. Subsequent figuring by hand with an even smaller sub-diameter tool, using the blending action of circular strokes, improves the surface smoothness tremendously and achieve a figure that approaches the limitations of the null testing aparatus.

For 12.5-inch and larger fast mirrors, I use a 5-inch diameter soft lap with facets narrowing toward the edge with a circular stroke to produce smooth, perfectly corrected surfaces. Although it is time consuming, armed with an accurate null test, any zone that can be seen can be removed with this technique.

If you test the roughed-in figure at this stage, the mirror appears to have a turned-down edge. In fact, there is no turned edge relative to the desired paraboloid — the figure simply hasn't made it out to the extreme edge yet.

With the small tool in hand and the mirror rotating slowly beneath me at about 1 to 5 r.p.m., I use a short circular stroke with the figuring tool's centre nearly over the edge of the mirror and slight hand pressure to spread the curve out to the edge, as shown in figure 2. I press the lap every five minutes or so and rotate it in my hand every few strokes to maintain its shape.

If the mirror is stationary, I move the polishing tool around the edge by hand. I figured three 12.5-inch f/5 mirrors with the mirror resting on a counter top and rotated often, and they are excellent performers. I must say that this is even more tiring than sitting at the machine as pictured.

Because the area of the figuring tool is small compared to the area of the zones it is working, the figure takes a long time to change with this technique. I have sat at the turntable for hours tweaking the 16-inch mirror's figure. Although the technique is tedious, it is extremely effective.

Slow polishing has significant advantages for the TM. If you misinterpret the figure from a test, you will probably catch your mistake before the figure gets too far out of hand. So painstaking a technique is hardly ideal for a commercial mirror maker trying to scratch a living by making telescope mirrors. Mirrors made this way certainly could never be sold profitably at today's cut-throat prices. Amateur telescope makers do have the time, and can afford to make very fine mirrors indeed.

As you figure it, the center of the mirror will rise as the edge is worn down. This must be corrected by applying a circular or elliptical stroke towards the center. Move the stroke centre in and out to avoid zones.

During these figuring steps the surface will dry up quickly. I use a plastic sprayer that produces a fine mist to wet the surface with water as evenly as possible. A Windex bottle is perfect. The polishing compound should not be allowed to dry while on the mirror because this will cause the lap to slip and grab during the stroke and may cause excessive sleeking (fine scratches) on the optical surface. Sleeks are not

An elliptical or circular stroke is used to bring the center down after a spell of working the edge. The arc motion helps prevent zoning. The center of the stroke is moved in or out depending on the degree of undercorrection.

uncommon on well figured mirrors since so much off-and-on work is done. Continuous polishing often produces a beautiful sleek-free surfaces because the polishing compound has time to break down and because the lap is in good contact with the surface.

As you work, keep in mind that the most important characteristic of a quality figure is smoothness especially towards the mirror's edge. Irregularities that lie inside the 70-percent zone are not as destructive as irregularities close to the edge. A 1/4-wave hole in the center will have little effect on the mirror's performance, but if the mirror suffers from a 1/4-wave edge roll, the mirror will be a disaster.

You can continue polishing and testing to the point where you can't see any zones. Provided the null tests inherent errors are very small, you can figure a mirror well past the point of practicality. Skilled observers can see the difference between 1/10-wave and 1/20-wave surfaces (that is, 1/5-wave and 1/10-wave wavefront accuracies, respectively). Smooth figures beyond 1/20th wave, although perhaps not necessary because of uncontrolable limitations like the atmosphere, are definitely achievable by the careful TM with the autocollimation test or with the Ross Null Test described in this issue of *Telescope Making*.

Testing with a null test is a lot like deep sky observing — the more you do it, the more you see. Although null tests are qualitative instead of quantitative, minute defects can be seen with a well made tester and an experienced eye. To quantify figure errors, I've mounted a dial indicator on the knife-edge slide of my tester and measured the difference in focus of various zones. If the mirror is bad, zonal differences are readily measured, and a measure of the wavefront quality obtained.

When the null is good, however, it is very difficult to quantify zonal errors. If I can polish out everything I can see I don't worry about quantifying anything as long as the residual error of the test set-up is small. If at all possible, I keep the Ross null residual smaller than 1/20-wave on the wavefront.

The 16-inch f/5 mirror and Ross lens with a 20-inch focal length lens pictured in this article has a residual wavefront error of about 1/50-wave. I hesitate to say that the mirror approaches this level of perfection because I have not had the oportunity to test the optics in an interferometer. However, I can confidently say that the surface is certainly better than 1/20-wave and very smooth.

One of the first things I learned in professional optics is that there are no absolutes. The technique described above is by no means the only way to figure a mirror. However, I have repeatedly employed it to make mirrors that were good enough to cause more than one refractor nut to yearn for a large, fast reflector. I encourage other TMs to try it.

I would like to thank Randy Pakan of Edmonton, Alberta for printing the photographs that accompany this story.

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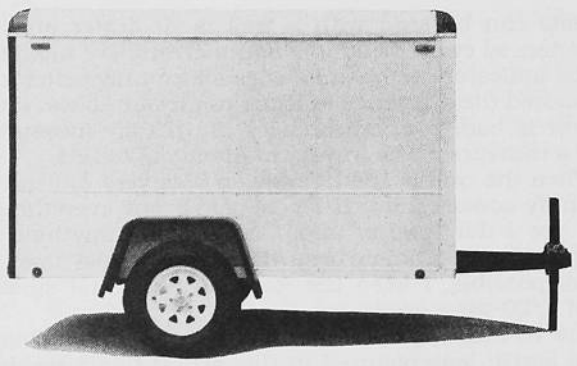

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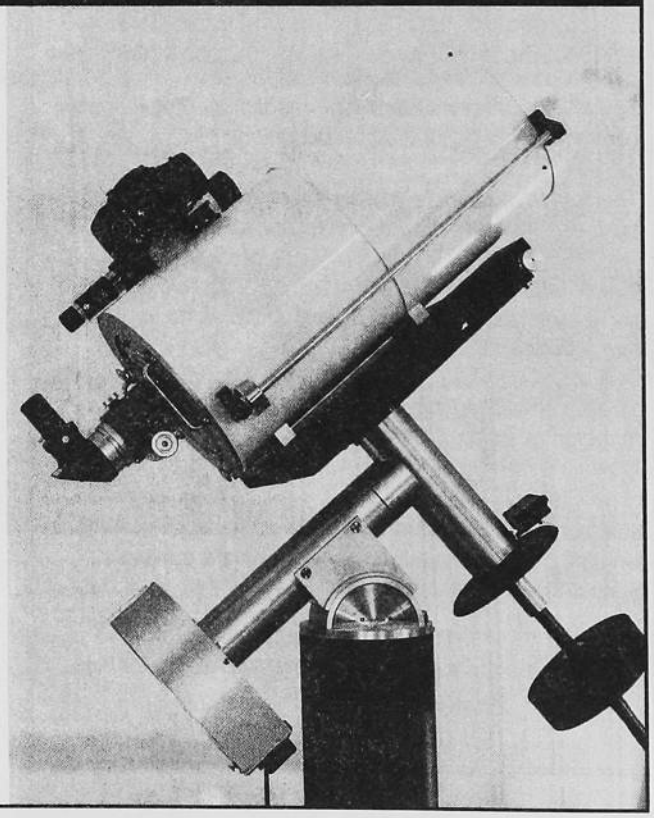

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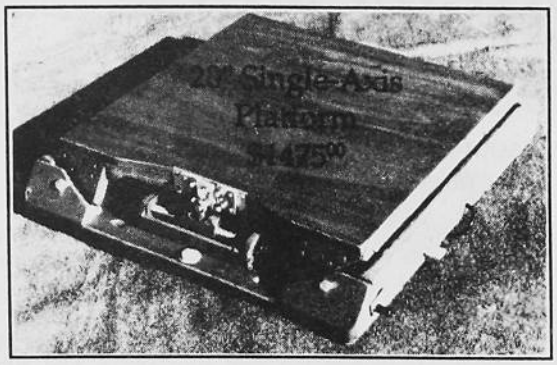

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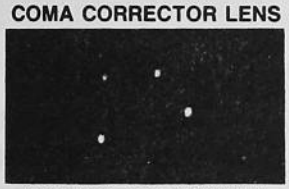

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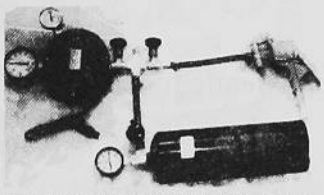

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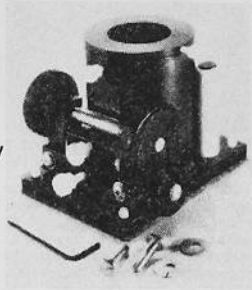

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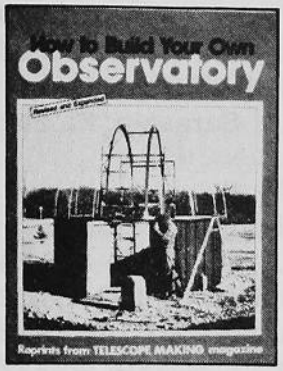

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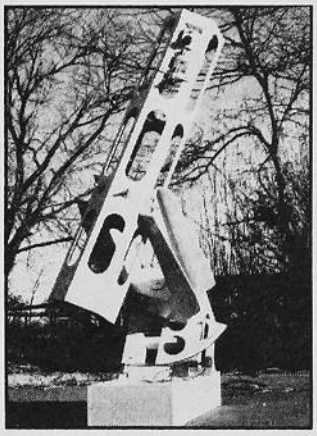

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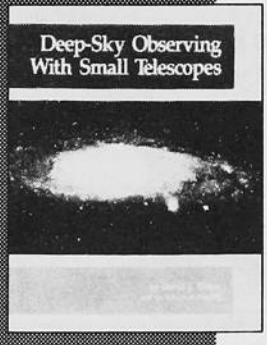

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